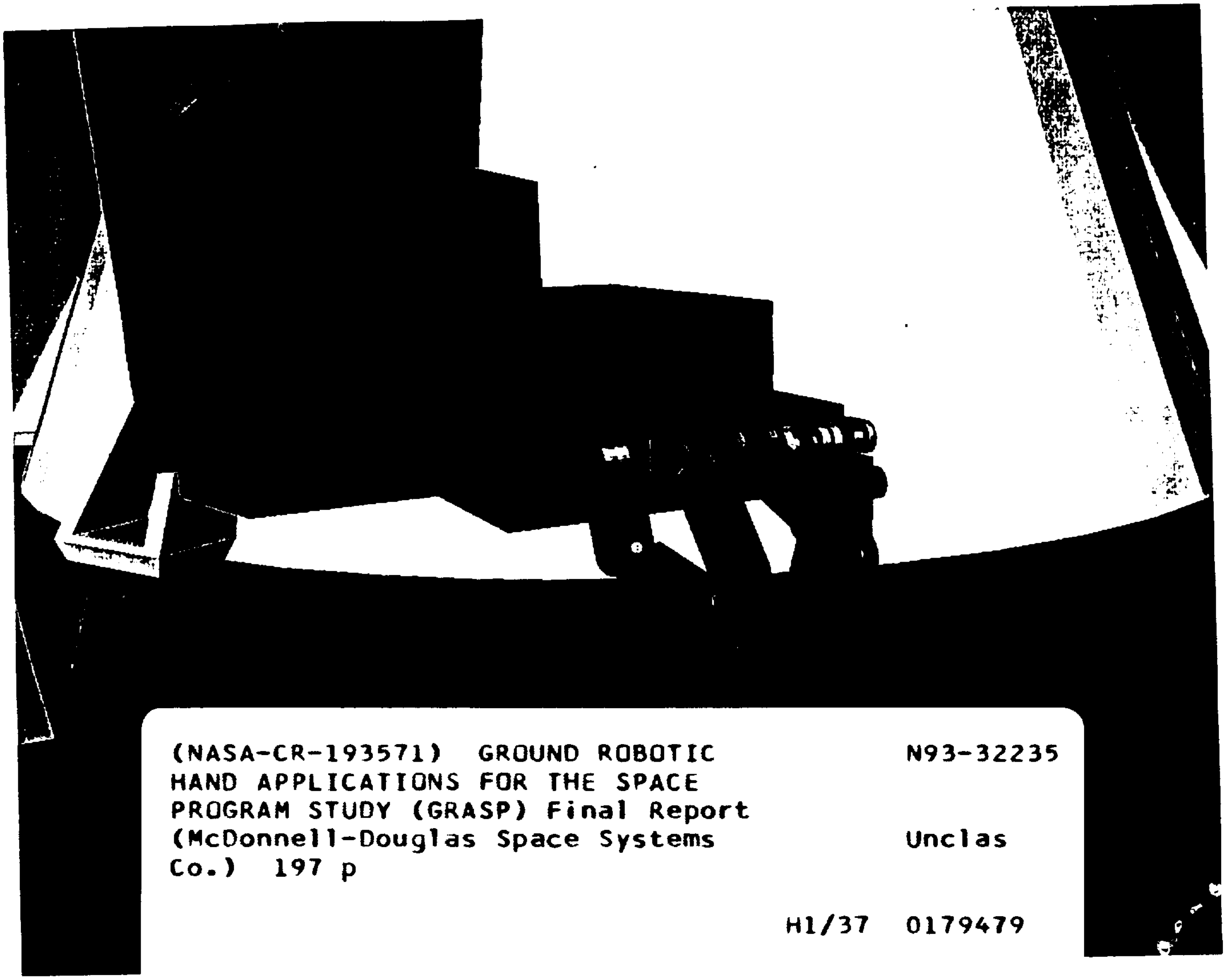

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Ground Robotic Hand Applications for the Space Program Study (GRASP)

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Final Report

April 1992

IN-37-CR

McDonnell Douglas Space Systems Company
Kennedy Space Center

Central State University

North Carolina A&T State University

P-197

EXECUTIVE SUMMARY

This document reports on a NASA-STDP effort to address research interests of the NASA Kennedy Space Center (KSC) through a study entitled, "Ground Robotic-Hand Applications for the Space Program (GRASP)." The primary objective of the GRASP study was to identify beneficial applications of specialized end-effectors and robotic hand devices for automating any ground operations which are performed at the Kennedy Space Center. Thus, operations for expendable vehicles, the Space Shuttle and its components, and all payloads were included in the study. Typical benefits of automating operations, or augmenting human operators performing physical tasks, include: reduced costs; enhanced safety and reliability; and reduced processing turnaround time.

The GRASP research was performed by a team comprised of the following three institutional participants:

Central State University (CSU)
Manufacturing Engineering Department
Wilberforce, Ohio

North Carolina A&T State University (NCA&T)
Mechanical Engineering Department
Greensboro, North Carolina

McDonnell Douglas Space Systems Company (MDSSC)
Kennedy Space Division
Advanced Automation Technologies Department
Kennedy Space Center, Florida

Program managers at the respective institutions were Dr. William A. Grissom (CSU), Dr. Shih-Liang Wang (NCA&T) and Dr. Michael Sklar (MDSSC). A Total of six faculty members and eight students at the two universities participated in the research. Dr. Grissom was designated overall principal investigator for the effort. Dr. Nader I. Rafla (CSU) edited the final report. Dr. Sklar of MDSSC played a major role in initially defining the NASA KSC research needs, in providing the primary technical interface between the external researchers and the KSC engineering and operations groups, and in providing technical and managerial guidance throughout the term of the project.

ACKNOWLEDGMENTS

The NASA GRASP research team wishes to thank the many individuals who contributed information for this study. Though the large number of contributors makes it impossible to acknowledge each individually, the names of some appear in the narrative of the report; others are included in an Appendix listing of contacts with an interest in dexterous robotics. Special thanks are due to those respondents who took the time and effort to complete and return the "Dexterous Robotic End Effector Survey."

The study could not have been completed without the generous support of the NASA employees and contractor personnel who provided the necessary information on ground based operations at the NASA Kennedy Space Center (KSC). Their hospitality and technical guidance during the on-site investigation by team members from Central State University (CSU), North Carolina Agricultural and Technical State University (NCA&TSU) and the McDonnell Douglas Space Systems Company - KSC (MDSSC) were greatly appreciated.

Special thanks are due to Mr. Eric Rhodes of Kennedy Space Center's Advanced Projects and Technology Office who served as technical monitor for the effort. Mr. Rhodes provided indispensable support in defining the scope of the study, providing technical guidance, and by arranging for needed KSC resources and expertise.

Finally, the investigation was made possible through the initiative of Dr. Lonnie Sharpe, director of the NASA Space Technology Development and Utilization Program (STDP) at NCA&TSU. Dr. Sharpe identified the area of mutual interest and assembled the NASA GRASP research team to carry out the study for NASA KSC. He also arranged for the project funding through the NASA STDP. The NASA GRASP research team, therefore, extends its sincere appreciation to Dr. Lonnie Sharpe and the NASA STDP program.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY ---------- i

ACKNOWLEDGEMENTS ---------- iii

TABLE OF CONTENTS ---------- iv

LIST OF FIGURES ---------- x

LIST OF TABLES ---------- xii

DEFINITION OF TERMS ---------- xiii

1. INTRODUCTION ---------- 1
    1.1 NASA STDP Program ---------- 1
    1.2 GRASP Research Team ---------- 1
    1.3 Study Objectives ---------- 2
    1.4 Report Overview ---------- 3

2. PREVIOUS STUDIES BY GRASP PARTICIPANTS ---------- 5
    2.1 Payload Processing System Study at KSC ---------- 5
    2.2 Central State University SLAVE² Hand ---------- 8
    2.3 References ---------- 13

3. TECHNOLOGY ASSESSMENT FOR SELECTED ROBOTIC END EFFECTORS ---------- 15
    3.1 Product Review: Conventional Grippers ---------- 15
    3.2 Product Review: Robotic Hands ---------- 21
        3.2.1 Sacros/Uni. of Utah Dexterous Robotic Hand ---------- 22
        3.2.2 Odetics Hand ---------- 22
        3.2.3 Omni-Hand (Ross-Heim) ---------- 24
        3.2.4 The DIGITS Finger ---------- 24
        3.2.5 The Harvard Hand ---------- 28
        3.2.6 Ames Research Center Prehensor ---------- 30
        3.2.7 Penn Hand ---------- 30
        3.2.8 Anthrobot-2 ---------- 33

3.2.9 Robot Digits -- 35
3.2.10 Scientific Research Associates Robot Hand -- 35
3.2.11 MIT Salsbury Hand -------------------------------- 36
3.2.12 Leuven (Belgium) Hands -------------------------- 36
3.2.13 Equalizer Manipulator ---------------------------- 37
3.2.14 University of California at Irvine/McCarth Finger ---------------------------- 37
3.2.15 USC-JPL Two Thumbed Dexterous Hand ------------------------------------ 42
3.2.16 Toshiba Hand (I) ------------------------------------ 44
3.2.17 Wright Robotic Hand ------------------------------ 44
3.2.18 Okada Hand --- 46
3.2.19 Belgrade Han -- 47
3.2.20 Mayland Modular Dexterous Hand ------------ 48
3.2.21 Southhampton Hand ------------------------------ 50
3.2.22 Utah/MIT Dexterous Hand ---------------------- 51
3.2.23 Stanford/JPL Hand -------------------------------- 58
3.3 Product Review: User Interface Devices -------------------- 61
3.3.1 VPL Research DataGlove --------------------------- 63
3.3.2 EXOS Dexterous Hand Master -------------------- 62
3.3.3 Arthur D. Little Sarcos Hand Master 63
3.3.4 MIMIC^{TM} Control Glove --------------------------- 63
3.3.5 Nintendo Power Glove ------------------------------ 66
3.3.6 Optical Pattern Hand Master ---------------------- 68
3.3.7 Rutgers Hand --- 68
3.3.8 Airmuscle Ltd. Teletact ----------------------------- 70
3.4 References -- 70

4. DEXTEROUS GRASPING AND MANIPULATION FUNDAMENTALS – 77
4.1 Introduction -- 77
4.2 Grasping Postures and External Loads ---------------------- 78
4.2.1 Two Contact Points -------------------------------- 79
4.2.2 Three Contact Points -------------------------------79
4.2.3 Four Contact Points-Planar External Force/Moment -------------------------- 81
4.2.4 Four Contact Points - 3D External Forces ------------------------------------ 83
4.2.5 Seven Contact Points ----------------------------- 83
4.3 Redundancy Analysis of Grasping Forces ------------------ 84
4.4 Conclusions -- 87
4.5 References --- 88

5. APPLICATION ASSESSMENT FOR COMMERCIAL MARKETS -------- 91
  5.1 Assessment Overview -------- 91
  5.2 Government Agency Related R&D Initiatives -------- 91
    5.2.1 National Aeronautics and Space Adminstration (NASA) -------- 92
    5.2.2 U.S. Department of Energy Office of Envirnomental research and Waste Management -------- 94
    5.2.3 U.S. Department of Energy Morgantown Energy Technology Center -------- 96
    5.2.4 U.S. Department of Energy U.S. Bureau of Mines Pittsburgh Research Center -------- 96
    5.2.5 U.S. Air Force Wright Laboratory Flight Dynamics Directorate -------- 98
    5.2.6 U.S. Air Force Wright Laboratory Manufacturing Technology Directorate-------- 99
    5.2.7 U.S. Air Force Wright Laboratory Armstrong Aeromedical Research Laboratory & Air Force Institute of Technology -------- 99
    5.2.8 National Science Foundation -------- 100
    5.2.9 Federal Aviation Administration -------- 100
    5.2.10 Army Research Office (ARO) -------- 100
    5.2.11 Office of Naval Research(ONR) -------- 102
    5.2.12 Woods Hole Oceanographic Institute -------- 102
    5.2.13 U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL) -------- 102
  5.3 Dexterous Robotic End Effector Survey -------- 104
    5.3.1 Objectives -------- 104
    5.3.2 Scope -------- 108
    5.3.3 Implementation -------- 108
    5.3.4 Summary of Results -------- 109
  5.4 References -------- 119

6. METHODOLOGY FOR ASSESSING GROUND PROCESSING APPLICATIONS ---- 121
6.1 Introduction ---- 121
6.2 Task Categories ---- 122
6.3 Evaluation Methods ---- 124
6.3.1 Information Compilation ---- 124
6.3.2 Evaluation Criteria ---- 126
6.3.3 Developing Dexterous Hand Requiremens ---- 129
6.3.4 Scoring Procedure ---- 130
6.4 References ---- 132

7. RESULTS OF NASA KSC GROUND PROCESSING APPLICATIONS ASSESSMENT ---- 133
7.1 Overview of KSC On-Site Review ---- 133
7.2 Overview of KSC Ground Processing Operations ---- 134
7.3 Preliminary Identification of Candidate Tasks ---- 135
7.4 Ground Processing Facility Operations Reviews ---- 139
7.4.1 Assembly Refurbishment Facility (ARF) ---- 139
7.4.2 Delta Launch Vehicle Complex ---- 140
7.4.3 Hanger AF ---- 140
7.4.4 Orbiter Processing Facility (OPF) ---- 142
7.4.5 Payload Changeout Room (PCR) ---- 144
7.4.6 Rotation, Processing and Storage Facility (RPSF) ---- 147
7.4.7 Vehicle Assembly Building (VAB) ---- 147
7.4.8 Operations and Checkout Building (O&C) ---- 149
7.4.9 Mobile Launch Platform (MLP) ---- 151
7.5 Evaluation Results ---- 152
7.6 References ---- 154

8. ROBOTIC HAND COMPUTER SIMULATIONS ---- 155
8.1 Overview ---- 155
8.2 Simulation Environments ---- 156
8.3 Hand Simulation (A & T) ---- 157
8.4 CSU - Computer Simulation ---- 158
8.5 MDSSC-KSC Robotic Hand End Cap Installation ---- 163
8.6 References ---- 166

9. CONCLUSIONS AND RECOMMENDATIONS ---------------------------- 169
9.1 Summary of GRASP Study Results ----------------------- 169
9.2 Current Dexterous Hand Capabilities Versus Requirements-- 171
9.3 Recommendations -- 172

10. APPENDICES

A. GROUND PROCESSING TASK DESCRIPTIONS
- A.1 Assembly Refurbishment Facility (ARF)
- A.2 Delta Launch Vehicle Complex
- A.3 Hanger AF
- A.4 Orbiter Processing Facility (OPF)
- A.5 Payload Changeout Room (PCR)
- A.6 Rotation, Processing and Storage Facility (RPSF)
- A.7 Vehicle Assembly Building (VAB)
- A.8 Operations and Checkout Building (O&C)
- A.9 Mobile Launch Platform (MLP)

B. GROUND PROCESSING TASK EVALUATION

C. DEXTEROUS ROBOTIC END EFFECTOR SURVEY
- C.1 Survey Instrument
- C.2 Mailing list

D. COMMERCIAL PRODUCTS SURVEY
- D.1 Mailing list
- D.2 Selected Brochure Information

LIST OF FIGURES

Figure 2.1 CSU SLAVE^2 Large Robotic Hand ---------- 9

Figure 3.1 Commercial Grippers - Source: Mecanotron, 6277 University Ave. N.E., Fridley, MN 55432 ---------- 16

Figure 3.2 Commercial Grippers - Source: Robotic Accessories, 6555 S. State Rt. 202, Tipp City, Ohio 45371 ---------- 17

Figure 3.3 Examples of Specialized Gripper Jaws - Source: Compact Air Products, Inc., P.O. Box 499, Westminster, SC 29693-0499 ---------- 17

Figure 3.4 Collat Jaws for Precision O.D. Gripping - Source: Robotics Accessories, 6555 S. State ---------- 18

Figure 3.5 Schematic of Single-Acting Vs. Double-Acting Grippers ---------- 19

Figure 3.6 Multi-task End-Effector Configured With More Than One Set Of Grippers ---------- 19

Figure 3.7 Typical Applications of the NKE Flexible Gripper ---------- 20

Figure 3.8 Sarcos/Univ of Utah Dexterous Robotic Hand ---------- 23

Figure 3.9 Oditics Hand ---------- 25

Figure 3.10 Omni Hand (Ross-Heim) ---------- 26

Figure 3.11 The Digits Finger Robotic Hand ---------- 27

Figure 3.12 Harvard Hand ---------- 29

Figure 3.13 Ames Research Center Prehensor ---------- 31

Figure 3.14 Penn Hand ---------- 32

Figure 3.15 Anthrobot-2 ---------- 34

Figure 3.16 MIT Salisbury Hand ---------- 38

Figure 3.17 Leuven (Belgium) Hands ---------- 39

Figure 3.18 University of California-Irvin/McCarthy Finger ---------- 40

Figure 3.19 USC-JPL Two-Thumbed Dexterous Hand ---------------------------- 43
Figure 3.20 Wright Robotic Hand -- 45
Figure 3.21 Maryland Modular Dexterous Hand ---------------------------------- 49
Figure 3.22 Utah MIT Dexterous Hand --- 52
Figure 3.23 Utah/MIT Hand in Various Grasp Configurations ------------------ 54
Figure 3.24 VPL Data Glove --- 62
Figure 3.25 EXOS Dexterous Hand Master -- 64
Figure 3.26 MIMC Control Glove --- 65
Figure 3.27 Nintendo Power Glove -- 67
Figure 3.28 Rutgers Portable Dexterous Force Feedback Master ------------ 69
Figure 3.29 Airmuscle Ltd. Teletact -- 71
Figure 4.1 Two Contact Points -- 80
Figure 4.2 Three Contact Points -- 80
Figure 4.3 Incorrect Arrangements of Three Contact Points ----------------- 80
Figure 4.4 Wrap-Around Grasp -- 82
Figure 4.5 Four Contact Points -- 82
Figure 4.6 Location of Four Contact Points -- 82
Figure 4.7 Four Contact Points -- 82
Figure 4.8 Four Contact Points 3D Forces --- 85
Figure 4.9 Pyramid Forces -- 85
Figure 4.10 Seven Contact Points --- 85
Figure 4.11 Location of Four Contact Points --- 86
Figure 4.12 Three Regions Defined by the Three Contact Forces ----------- 86
Figure 7.1 Horizontal Payload Processing Flow -------------------------------- 136
Figure 7.2 Vertical Payload Processing Flow ----------------------------------- 137
Figure 7.3 Mixed Payloads Processing Flow ------------------------------------ 138

Figure 7.4 Orbiter Processing Facility (OPF) ---------------------------------- 143
Figure 7.5 Payload Changeout Room (PCR) ---------------------------------- 145
Figure 7.6 Payload Ground Handling Mechanism (PGHM) Structure ----- 146
Figure 7.7 Vehicle Assembly Building (VAB) ---------------------------------- 148
Figure 7.8 Operations and Checkout Building (O&C) ------------------------ 150
Figure 8.1 NCA & TSU Hand Model --- 159
Figure 8.2 CSU SLAVE^2 Finger Model -- 160
Figure 8.3 Three-Finger CSU/NASA Hand with a Fully Stretched Arm -- 162
Figure 8.4 Three-Point Contact Grasping of a Cylinder ---------------------- 164
Figure 8.5 Assembly of the Space Shuttle Aft Skirt with the hand-arm mounted on an overhead crane -------------------------------------- 165
Figure 8.6 MDSSC Model of Anthrobot-2 Hand ------------------------------ 166

LIST OF TABLES

Table 5.1 Survey Results for Current Operations ----------------- 111

Table 5.2 Survey Results for Potential Future Operations ------- 112

Table 5.3 Ranking of Dexterous Processing Functions ----------- 113

Table 5.4 Ranking of Operation Criteria ------------------------------ 114

Table 5.5a Performance Requirements for Application Within Universities ----------------------------- 115

Table 5.5b Sensor/Vision Requirements for Application Within Universities ----------------------------- 116

Table 5.5c Performance Requirements for Application Within Universities ----------------------------- 117

Table 5.5d Sensor/Vision Requirements for Application Within Universities ----------------------------- 117

Table 6.1 Task Categories --- 123

Table 6.2 Information Areas -- 125

Table 6.3 Criteria Description -- 126

Table 6.4 Operational Criteria -- 127

Table 6.5 Technological Criteria ------------------------------------- 129

Table 6.6 Dexterous Robotic hand Design Requirements -------- 131

Table 7.1 Operations Personnel -- 134

Table 7.2 Candidate Task List -- 155

Table 8.1 Simulation Hardware and Software Used -------------- 156

DEFINITION OF TERMS

2D	Two Dimensional
3D	Three Dimensional
ARF	Assembly and Refurbishment Facility
ARO	Army Research Office
AARS	Autonomous Robotics Refueling System
ASME	American Society of Mechanical Engineers
BOM	Bureau of Mines
CCAFS	Cape Canaveral Air Force Station
CCD	Charge Coupled Device
CERL	Construction Engineering Research Laboratory
CII	Construction Industry Institute
cm	Centimenter
CSU	Central State University
DARPA	Defense Advanced Research Projects Agency
DC	District of Columbia
dc	direct current
DHM	Dexterous Hand Master
DM	Disassembly Manual
DOD	Department of Defense
DOE	Department of Energy
DOF	Degrees of Freedom
DOT	Department of Transportation
FSE	Flight Support Equipment
FY	Fiscal Year
gm	Gram
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HAIR	HEPA Aerial Inspection Robot
HCC	Hand Controller Computer

(Continued)

DEFINITION OF TERMS (Continued)

HEL	Human Engineering Laboratory
HEPA	High Efficiency Particle Air Accumulator
HPF	Hazardous Processing Facility
Hz	Hertz
I-DEAS	Integrated Design and Engineering Analysis System
IEEE	Institute of Electrical and Electronic Engineers
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
kg	Kilogram
KSC	Kennedy Space Center
LAN	Local Area Network
LaRC	NASA Langley Research Center
LLCS	Low Level Control Systems
LPS	Launch Processing System
LSC	Linear Shaped Charge
LSSP	Launch Site Support Plan
M-DOF	Multiple Degrees of Freedom
MDSSC	McDonnell Douglas Space Systems Company
MHEHP	Material Handling Equipment Handling Programs
MHRT	Material Handling Research Test
MHz	Megahertz
MIMIC	M-DOF Integrated Master Interactive Control
MIT	Massachusetts Institute of Technology.
MLP	Mobile Launch Platform
mm	Millimeter
MoMan	Mobile Manipulator
MPa	Mega Pascals
N	Newton
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NCA&TSU	North Carolina Agricultural and Technical State University
NIST	National Institute of Science and Technology

(Continued)

DEFINITION OF TERMS (Continued)

NiTi	Nickel Titanium
N-mm	Newton-millimeters
NTIS	National Technical Information Service
OBR	Ohio Board of Regents
O&C	Operations and Checkout
O.D.	Outside Diameter
OM	Operations Manual
OMI	Operations and Maintenance Instruction
OMRF	Orbiter Maintenance and Refurbishing Facility
ONR	Office of Naval Research
ONRL	Oakridge National Laboratory
OPF	Orbiter Processing Facility
PCR	Payload Changeout Room
PGHM	Payload Ground Handling Mechanism
POOC	Payload Operations Control Center
PPF	Payload Processing Facility
PPS	Payload Processing System
PPSS	Payload Processing System Study
PRDA	Program Research and Development Announcement
PS6A	Nintendo Power Glove Series Adapter
PSIG	Pounds Per Square Inch Gauge
RCC	Remote Compliance Center
R&D	Research and Development
RPSF	Rotation Processing and Storage Facility
RSS	Rotating Service Structure
SBIR	Small Business Innovative Research
SDRC	Structural Dynamics Research Corporation
SMA	Shape Memory Alloy
SRB	Solid Rocket Booster
SSME	Space Shuttle Main Engine
STDP	Space Technology Development and Utilization Program
STS	Space Transportation System
TDRS	Tracking Data and Relay Satellite

(Continued)

DEFINITION OF TERMS (Continued)

TM	Trade Mark
TPS	Thermal Protection System
TSD	Transensory Devices
UARS	Upper Atmosphere Research Satellite
UPenn	University of Pennsylvania
USBI	United States Boosters Inc.
USC	University of Southern California
VAB	Vehicle Assembly Building
VDC	Volts Direct Current
VPF	Vertical Processing Facility
VPL	VPL Corporation
WPAFB	Wright-Patterson Air Force Base

CHAPTER 1

INTRODUCTION

1.1 NASA STDP Program

North Carolina Agricultural and Technical State University (NCA&T) was selected by the National Aeronautics and Space Administration (NASA) as the Center for its Space Technology Development and Utilization Program (STDP) in 1989. The overall goal of STDP is to achieve increased participation by minority academic institutions and small and disadvantaged businesses for NASA research initiatives. Central State University in Wilberforce, Ohio was one of the four minority universities selected to join NCA&T as a charter member of the STDP consortium. The program was designed to involve major high technology corporations, minority businesses and minority academic institutions to achieve enhanced technology transfer, particularly with respect to the minority community. One of the major objectives was to increase the pool of talented, experienced minority researchers to support NASA objectives. The STDP program is fulfilling its mission by proposing and carrying out research and development efforts needed by the various NASA centers. This document reports on one such effort to address specific research interests of the NASA Kennedy Space Center (KSC) through a study entitled, "Ground Robotic-Hand Applications for the Space Program (GRASP)."

1.2 GRASP Research Team

The GRASP research was performed by a team comprised of the following three institutional participants:

Central State University (CSU)
Manufacturing Engineering Department
Wilberforce, Ohio

North Carolina A&T State University (NCA&T)
Mechanical Engineering Department
Greensboro, North Carolina

McDonnell Douglas Space Systems Company (MDSSC)
Kennedy Space Division
Advanced Automation Technologies Department
Kennedy Space Center, Florida

Program managers at the respective institutions were Dr. William A. Grissom (CSU), Dr. Shih-Liang Wang (NCA&T) and Dr. Michael Sklar (MDSSC). Dr. Grissom was designated overall principal investigator for the effort. Dr. Sklar of MDSSC played a major role in initially defining the NASA KSC research needs, in providing the primary technical interface between the external researchers and the KSC engineering and operations groups, and in providing technical and managerial guidance throughout the term of the project.

Other key participants from CSU were faculty members Dr. Abayomi J. Ajayi-Majebi, Dr. Morris M. Girgis, Dr. Nader I. Rafla, and Mr. John H. Sassen. Mr. Brian Richardson of MDSSC played a major role in performing this study. Student participants were Mr. Felipe Mesa, Mr. Keith Robinson and Mr. Timothy Brennaman of CSU and Mr. Charles McCollough, Mr. Derrick Giles, Mr. Jingxi You and Ms. Stacy Burns at NCA&T.

Mr. Eric Rhodes, located at Kennedy Space Center's Advanced Projects and Technology Office, served as technical monitor for the effort. He provided indispensable support in identifying the KSC research needs, developing a properly focused statement of work, establishing KSC technical contacts and providing needed KSC resources and technical guidance.

1.3 Study Objectives

The primary objective of the GRASP study was to identify beneficial applications of specialized end-effectors and robotic hand devices for automating any ground operations which are performed at the Kennedy Space Center. Typical benefits of automating or augmenting human operators performing physical tasks include reduced costs, enhanced safety and reliability and reduced processing turnaround time. Note, this study is unique in that it includes only those tasks which involve dexterous human manipulations, not all physical processing tasks. However, the processing operations and tasks included within the scope of this study include all physical processing associated with any spacecraft or payload handled at KSC. Thus, operations for expendable vehicles, the Space Shuttle and its components, and all payloads are included.

The specific objectives of this study include:

1. Develop a complete, stand alone methodology for assessing ground processing operations for dexterous, automated systems.
2. Evaluate the capabilities of commercially available, and laboratory based robot hand devices.
3. Evaluate the control issues and determine control methods which will allow for precise control of hand-like systems.
4. Evaluate robotic hand needs within commercial applications.
5. Recommend attractive applications for robotic hand operations and develop technology requirements for KSC applications.
6. Develop preliminary concepts of robot hand implementations and demonstrate through computer animations.

One additional objective of the study, which is true for all STDP funded projects, was to involve minority universities in transferring their technology to NASA and gaining an improved awareness of technological needs and real-world problems at NASA. The study provided an opportunity for minority universities Central State and NCA&T State University, to gain an increased awareness and much better understanding of spacecraft ground operations at KSC. Moreover, the close working relationship between the universities and MDSSC also provided mutual benefits.

1.4 Report Overview

This report is presented in nine chapters and an appendix section containing related material. Chapter 2 briefly reviews prior research and development by the participants regarding KSC ground based operations and dexterous robotic hands. Chapter 3 describes existing laboratory or commercial grippers, dexterous robotic hands and interface devices. Chapter 4 presents grasping and manipulation fundamentals from a theoretical point of view. Chapter 5 summarizes an investigation of robotic hand developments and results of a formal survey of dexterous robotic end-effector applications by industry, university and government agency users. Chapter 6 describes the formal methodology which was developed to rank the level of potential gains for various ground based operations through the increased application of dexterous end-effector devices. Chapter 7 describes the ground based operations review procedure and summarizes the results of applying the assessment methodology for various candidate operations. Chapter 8 describes the approaches used by the three participating institutions to develop dexterous end-effector simulation models and focuses on the MDSSC simulation for one particularly promising application involving the Solid Rocket Booster (SRB) aft skirt assembly. Chapter 9 briefly reviews the GRASP study results and discusses conclusions and recommendations.

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CHAPTER 2

PREVIOUS STUDIES BY GRASP PARTICIPANTS

The selection of MDSSC, CSU and NCA&T as team members for the NASA GRASP research was based in large measure upon their prior relevant experience in mechanism, robotics and automation studies. MDSSC had recently participated in a comprehensive study to determine attractive applications of physical automation and robotic systems for Space Shuttle payload operations at KSC. The study reported in a 1990 Final Report [2.1] is described briefly in Section 2.2.1. This experience was augmented by extensive MDSSC facilities and resources at the Kennedy Space Center site and an in-depth knowledge of KSC ground based operations. These factors ideally suited MDSSC for the GRASP study.

Likewise, CSU had previously performed highly relevant work as part of ongoing efforts at the University to develop a large master slave controlled dexterous robotic hand with support from NASA KSC and JPL. CSU's 1989 Phase I Final Report [2.2] for this effort included an extensive product and literature review related to robotic hand design, grasping theory and control hardware and software. The work is described further in section 2.2.

Finally, NCA&T with a strong interest and ongoing studies in kinematics, mechanisms and grasping/manipulation theory brought an additional strength to the team as reflected in Chapter 4 of this report.

2.1 Payload Processing System Study at KSC

In 1990, an extensive study was performed to determine attractive applications of physical automation and robotic systems for Space Shuttle payload operations at KSC. Payload operations refer to all activity associated with receiving, assembling, testing, installing and deintegrating all cargo to be carried by the shuttle on each mission. Thus, the study did not include the activities associated with processing the shuttle vehicle itself or activities related to processing the other vehicle components such as the Solid Rocket Boosters (SRB's) and External Tanks. The study was directed by the KSC Development Engineering (DE) - Mechanical Engineering Special Projects Branch and the KSC Advanced Projects Office. Funding for the activity was provided by NASA's Office of Aeronautics and Exploration Technology telerobotics program (Code RT). The study was carried out by a team consisting of the following contractors, NASA and University groups:

NASA-KSC Mechanical Engineering - Special Projects Branch

NASA-KSC Advanced Projects Office

Boeing Aerospace Operations

MDSSC Advanced Product Development

Carnegie Mellon University Field Robotics Center

NASA-Langley Research Center

In addition to these organizations, consisting mostly of automation and robotics technologists, operations personnel who are involved in day to day payload tasks were also included. The study focused on all physical tasks required for five specific shuttle payload missions, and generic tasks performed in three main processing facilities. The facilities included the Operations and Checkout highbay where horizontal payloads are processed, the Vertical Processing Facility where vertical payloads are processed, and the Payload Changout Room (PCR) where all payloads are processed while at the launch pad. The specific missions were chosen to encompass all of the typical types of payloads flown by the Shuttle. Typical mission payloads include: cargo bay pallet instruments, orbital and planetary spacecraft, spacelab modules, and communication satellites. A further understanding of these terms and operations can be obtained from Section 7.2 which provides an overview of KSC processing operations. The study effort is documented fully in a FY1990 Final Report [2.1].

The primary objective was to identify specific tasks and mission operations which could benefit from automated systems due to cost savings or overall process improvements. Using automated systems to either replace or simply augment human operators could improve cleanliness and task reliability, and could reduce potential hazards to both the operators and the spacecraft equipment. In addition to identifying attractive automation applications, attempts were also made to justify and document the benefits and develop preliminary concepts for each of these. A complete methodology for evaluating potential automation benefits was developed in close cooperation with operations personnel. This methodology was then applied in the evaluation of numerous mission processing and facility operations tasks. A complete ranking of all physical processing tasks associated with the above stated missions and facilities was produced.

The most attractive applications which were later pursued in greater detail included:

1. PCR ceiling HEPA Filter Inspection
2. PCR Interstitial area washdown
3. PCR Inspection and Processing

Note that all of the most attractive tasks to be automated occur at the launch pad Payload Changout Room. The PCR is an enclosed, clean-room processing facility which is part of the Rotating Service Structure. This facility is used to access payloads placed in the orbiter before it is brought to the pad, or to process and transfer payloads into the orbiter after it arrives at the pad. Due to the fact that this is a moveable, and thus relatively small facility, payload access is limited in comparison with the other large payload facilities such as the O&C and the VPF. Also, all missions involve activities in the PCR. Moreover, all PCR tasks are performed just before launch and are therefore extremely time critical. Thus, because there are a greater number of constraints and difficulties associated with the PCR than other facilities, the PCR applications tend to be more promising as automation candidates.

The results of this prior study have shown that there are physical applications within KSC payload processing which would benefit from the use of automated systems. It is likely that there are an even greater number of attractive automation applications involved in overall vehicle processing. All three payload and facility applications identified are now being pursued further. Funding for the HEPA Filter Inspection system has been provided by the Telerobotics program. The system, which is called the HEPA Aerial Inspection Robot (HAIR) is now being developed and will be ready for testing in late 1992. This system is expected to become operational in the near future. The other two applications have been considered further. The Inspection and Processing Robot (Referred to as M-DOF in the study) will be the focus of a detailed system study and conceptual design effort scheduled to begin in FY93.

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2.2 Central State University (SLAVE^2) Hand

Central State University in Wilberforce, Ohio, is currently developing a large, anthropomorphic, master/slave-controlled, robotic hand [2.2] through a joint funding by the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), and the Ohio Board of Regents (OBR). The envisioned device would be larger and more powerful than the human hand while possessing sufficient dexterity to closely mimic the fingering and grasping configurations and operations of its human counterpart. Work on the dexterous hand which began about three years ago is currently in its second phase of incremental refinement and upgrade from a single finger control to the control of two fingers and a thumb as shown in Figure 2.1.

Design Objectives - The CSU hand has been assigned the acronym, SLAVE^2, for "Servomotor-Linked Articulated Versatile End Effector", reflecting the planned master/slave control operational mode, and the use of an individual electric servomotor to drive each joint. The hand could find application in a variety of special situations or risky operations, including the handling of hazardous wastes, munitions, or large radioactive or chemically contaminated objects. Fire fighting, construction, demolition, mining, disaster clean-up, and rescue operations might provide additional applications for a large dexterous end effector operated remotely under master/slave control.

Component Selection/Design Tradeoffs - A rapid prototype R & D strategy, utilizing off-the-shelf components wherever possible, was used in the development of the SLAVE^2 prototype. A key goal of the strategy was to minimize development time and costs by eliminating long lead times for design and construction of individual components. The commercial availability of components, including the electric servomotors and power transmission mechanisms used to drive the individual finger joints, dictated the size, weight, payload and finger length of the hand assembly.

Design Characteristics - Based upon this consideration and current design estimates, the initial dexterous robotic hand model will be approximately four times human size with an overall hand length of approximately three feet (0.9 m) and an individual fingertip clamping force of 10-12 pounds (44 - 53 N). It is expected that the finger length will be about 18 inches (46 cm), and weigh approximately 15 pounds (6.8 kg). Initial estimates indicate that a frequency response of 0.5 Hz can be achieved.

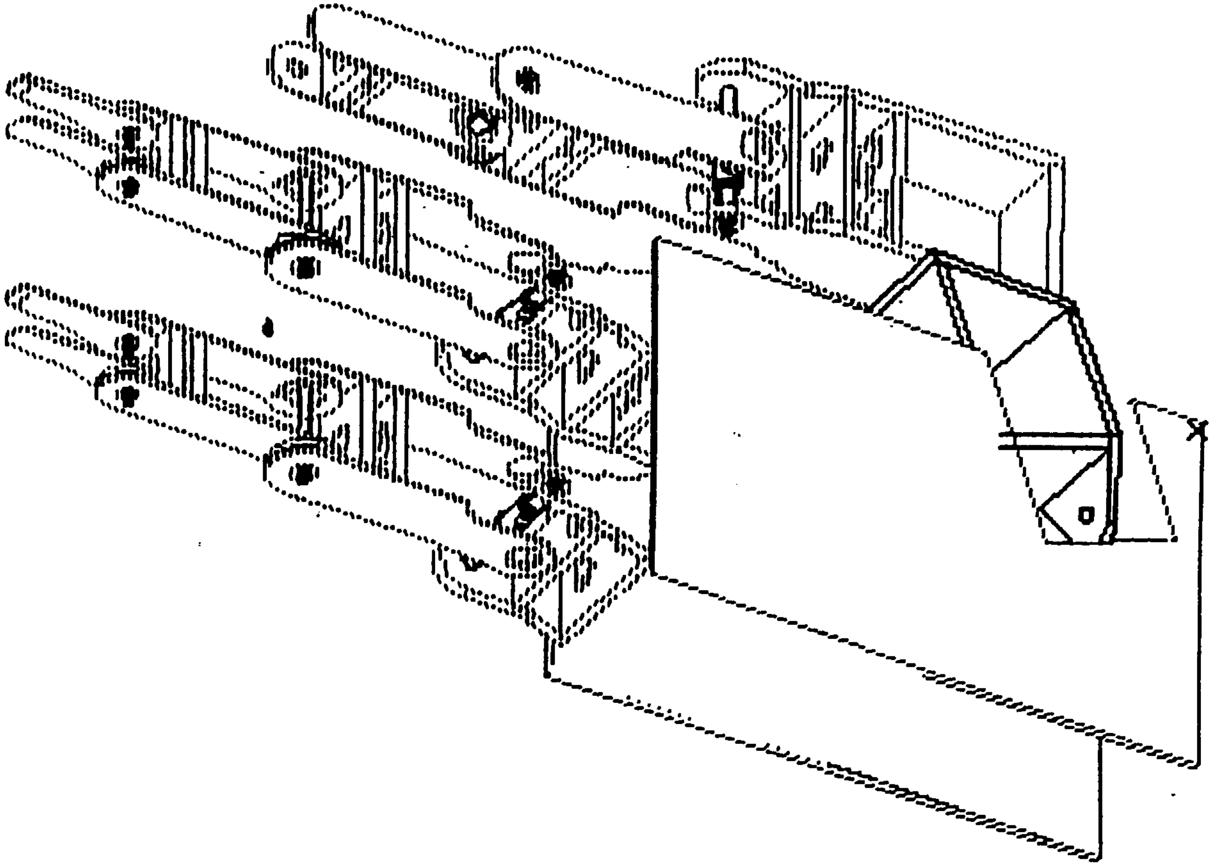

Figure 2.1 - CSU SLAVE^2 Large Robotic Hand

Mechanical Configuration - Originally a mechanical hand configuration possessing four fingers and a thumb, each with four joints or degrees-of-freedom, was considered. More specifically, for each finger/thumb member, three joints provide flexion and extension (and possibility hyperextension), and a fourth joint allows abduction and adduction. For a hand with four fingers and a thumb this would give a total of twenty degrees of freedom and provide sufficient dexterity to closely replicate the gripping and fingering actions of a human hand. More recently, the design goal has been simplified to a twelve degree of freedom configuration possessing a thumb, index finger and middle finger.

The first phase of the research effort involved the development of a working laboratory prototype of a single four degrees-of-freedom finger. Initial emphasis was placed upon selection of the most desirable mechanical configuration for the compound knuckle joint which provided for both abduction and adduction motions. In deciding on a prototype design, a number of different mechanical configurations were considered and evaluated, using a value analysis criteria for evaluating the various alternative configurations [2.3]. The value analysis factors included:

1) Motors on palm
2) Coincidence of abduction/adduction axes
3) Symmetry about finger/palm
4) Independence of drive axes
5) Compactness
6) Weight
7) Complexity vs. simplicity
8) Number of right angle drives required
9) Range of flexion/extension
10) Range of abduction/adduction
11) Torque (Flexion/Extension)
12) Torque (Abduction/Adduction)
13) Mounting rigidity
14) Assembly alignment ease
15) Commercial components availability
16) Producibility

While other important factors such as cost, reliability, maximum payload, frequency response, and speed are more difficult to quantify at the early design stage, and therefore do not appear explicitly in the value analysis, they are however reflected indirectly by one or more of the value analysis factors. In the value analysis, for example, one key significance of having the drive motors mounted on the palm (Value analysis factor 1), instead of on the moving digits, is to minimize the inertia of the moving finger, and thus optimize the frequency response and speed. Likewise, torque levels (Factors 11 & 12) relate directly to the maximum load capacity, while factors such as commercially available components (Factor 15), and producibility (Factor 16) have a direct impact on cost and reliability.

Drive Component Selection - The drive components needed to power the finger joints were selected, keeping in mind the desire to achieve optimum performance and compactness while utilizing commercially available components to the greatest extent possible. Consequently, the design work included the balancing of the load capacity of the servomotors, gear reducers, and right angle drive units. The drive configuration alternatives, when evaluated on the basis of torque capacity-to-density ratio (a proxy for weight and compactness) provided an interesting result, the right angle drive units surprisingly proved to be the limiting factor in achieving greater payloads.

Servomotors - Each of the twenty joints is directly driven by an independent brushless DC servomotor, and an integrated speed reducing mechanism. Although practical brushless DC servomotors are a relatively recent development triggered by advances in solid state electronics and permanent magnet technology, units are now available from a number of major manufacturers. The selection of 24 volt DC brushless motors from the Inland Motor Division of Kollmorgen Corporation was based upon high torque-to-density ratios and the convenient operating voltage range.

The brushless DC type of servomotor duplicates the external performance of a conventional DC motor without utilizing a commutator or brushes. This is possible because solid-state electronic switching replaces the conventional brush commutation switching process. A second major difference is that the wound member, or armature, reverses its role and relative position from rotor (rotating member) and inner component in the conventional DC motor to stator (stationary member) and outer component in the brushless motor. These two differences lead to a number of significant advantages for the brushless DC motor with respect to performance, safety and reliability :

1. No brushes to wear out: increased reliability, reduced maintenance requirements.
2. No commutator bars to oxidize: ability to sit idle for years without loss of performance.
3. Absence of brush arcing: safer in the presence of fumes, dust, paint spray, etc.
4. Speeds up to 80,000 RPM are practical.
5. Less radio-frequency interference.

6. Easier cooling of windings with fins or cooling jacket: extended operating range.
7. Smaller diameter, more compact.
8. Reduced inertia: increased acceleration and improved control.

Power Transmission - Electric motors characteristically produce relatively low torque in the low speed range. This is true as well for brushless DC motors; furthermore preliminary calculations indicate that torque multiplication (or speed reduction rates in the range of 80/100:1) will be required to achieve the desired robotic hand strength. To meet this requirement, the patented harmonic drive gearing device available from the Harmonic Drive Division of the Emhart Machinery Group, Wakefield, MA, was selected.

The unique design of the harmonic drive with three simple concentric components yields the following advantages for robotics gear reduction applications:

1. Exceptionally high torque and power capability in a small package.
2. Essentially zero backlash.
3. Efficiencies as high as 90%
4. Ratios as high as 320:1 in a single reduction with much higher ratios achieved by compound stages.
5. Concentric input and output shafts.
6. No radial loads, since torque is generated by a pure couple; this simplifies the supporting structure requirements.

A few drawbacks of the harmonic drive include its relative compliance, leading to its exhibiting a soft windup characteristic in the low torque region. In this region it produces a small, sinusoidal positional error on the output, which varies inversely with the pitch diameter at a predominant frequency of twice the input speed. Additionally an amplitude modulation typically occurs twice per output revolution.

A detailed explanation of the operating principles is given in the "Harmonic Drive Designers Handbook" (3.51) along with load and accuracy ratings, operating life expectancies and installation and servicing guidelines.

In view of the need to maintain a slender aspect ratio in the design of the finger configuration, it was necessary to utilize a right angle drive mechanism to provide torque about an axis perpendicular to the axis of the servomotor-harmonic drive assembly. For this purpose spiral bevel gears manufactured by the Arrow Gear Company of Downers Grove, Illinois were selected. This type of gearing features efficient and smooth operation and relatively high strength.

Electronic Programmable Controllers - With the many degrees of freedom required for dexterous robot hands, the problem of control and demand on computing escalates. The simplest approach is to use a local control loop for each joint. However, for precise motion control, a coordinated motion for fingers and digits becomes a must for an efficient design.

For master-slave operation, the coordination is achieved by the action of a human in the loop. Currently, a number of high performance servomotor controllers are commercially available. These controllers are designed to be programmable and installed in personal computers.

The Galil DMC/600 series Advanced Motion Controller has been selected to fulfill this role in the finger prototype development. The DMC/600 is a fully programmable servo motion controller contained on an IBM PC compatible card. It controls the motion of up to three DC motors with incremental encoder feedback. Modes of motion include independent or vector positioning, contouring, jogging and homing. A FIFO buffer allows fast pipelining of instructions. The DMC-600 contains a digital filter with an integral gain term for eliminating position error at stop. Several error handling features are available including automatic shut-off for excessive position error, limit switch inputs, emergency stop inputs and programmable torque limits.

2.3 References

2.1 Rhodes, E. et al., "Payload Processing System Final Report", NASA-KSC Publication KSC-DM-3489, October 1990.

2.2 Grissom, et al., "Technology Assessment of Robotic Hands," Final Report, Vol. 1, Executive Summary, JPL Contract No. 958292., October 1989.

2.3 Grissom, W. A., Abd-Allah, M. A., White, C. L., "Concept for a Large Robotic Hand," Proceedings of the Second Annual Workshop on Space Operations Automation and Robotics (SOAR '88), NASA Conference Publications 3019, pp. 353-359, July 20-23, 1988.

CHAPTER 3

TECHNOLOGY ASSESSMENT FOR SELECTED ROBOTIC END-EFFECTORS

3.1 Product Review: Conventional Grippers

As part of the GRASP study, product catalogs were solicited from vendors who supply conventional grippers for use as robotic end-effectors or for more conventional automated material handling applications. Several of the vendors are listed in Appendix D.2. The information gathered indicates that a wide variety of such commercial devices is available. These devices can be purchased as off-the-shelf standard items to satisfy many applications or as custom designs for more specialized use. Brief excerpts of the catalog information follow.

Grippers are classified by type of gripping action (e.g., parallel, angular/scissor, collat, single acting, double acting, etc.), number of gripping jaws (two, three, or four, etc.), and actuating source (hydraulic, pneumatic, electromagnetic, etc.). Examples of some typical commercially available grippers are given in Figures 3.1 and 3.2. In many applications specially shaped jaws can be affixed to the gripper heads to provide for gripping of a specific shape. Four types of jaws are illustrated in Figure 3.3. Figure 3.4 shows a collat gripper which provides for precise gripping of parts with accurate outside diameters. For some applications, objects can be most conveniently held by a magnetic head, vacuum head or suction cup.

In some cases a double acting gripper is employed to satisfy the need to pick up more than one type of part. A schematic of single and double acting grippers is shown in Figure 3.5. Often an end-effector is configured with more than one set of grippers as shown in Figure 3.6 to accomplish multitask operations in a sequential manner.

The Jergens NKE Flexible Gripper shown in Figure 3.7 is an interesting variation of the more common grippers and illustrates how a single device might accomplish several different functions.

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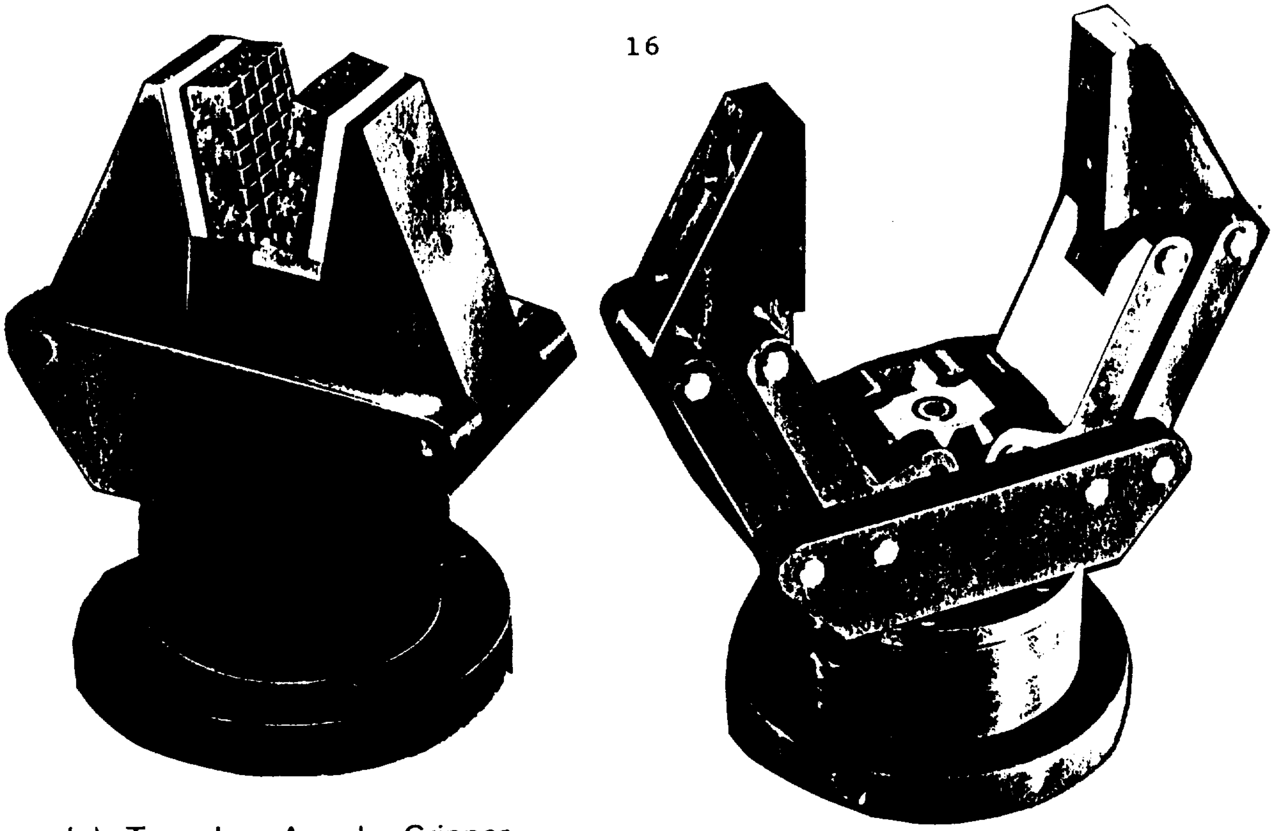
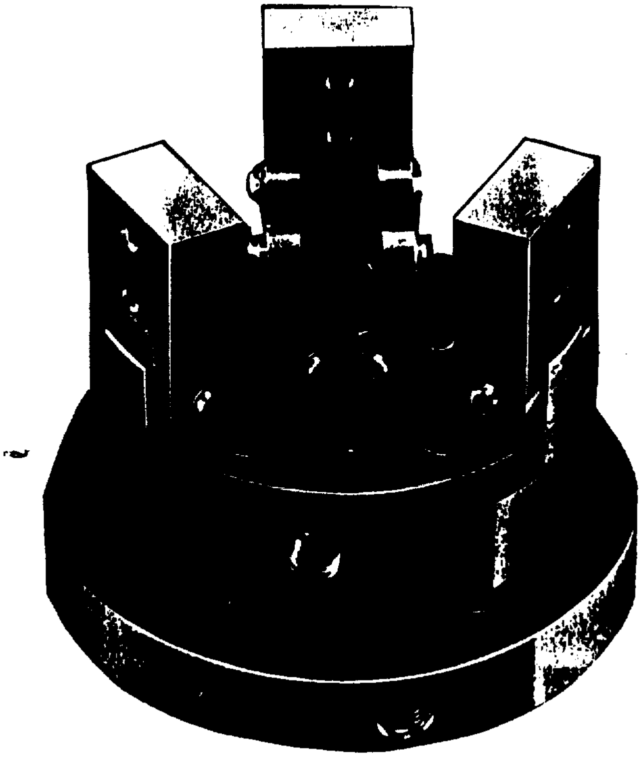


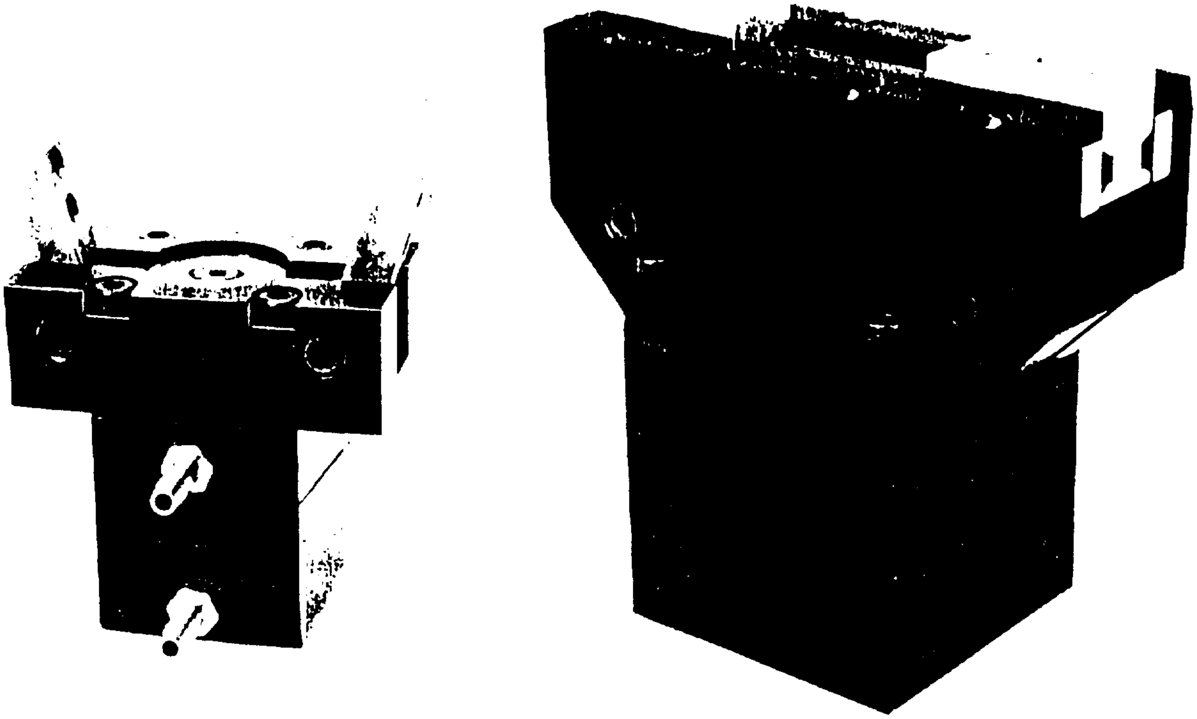
(a) Two-Jaw Angular Gripper

(b) Two-Jaw Parallel Gripper

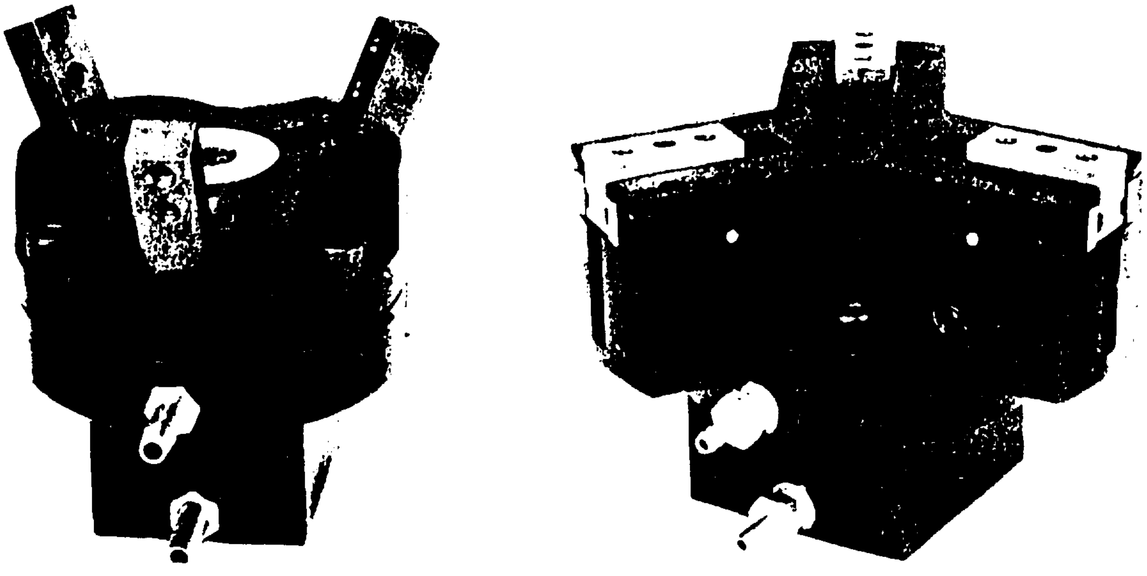


(c) Three-Jaw Angular Gripper

Figure 3.1 Commercial Grippers - Source: Mecanotron,
6277 University Ave. N.E., Fridley, MN 55432

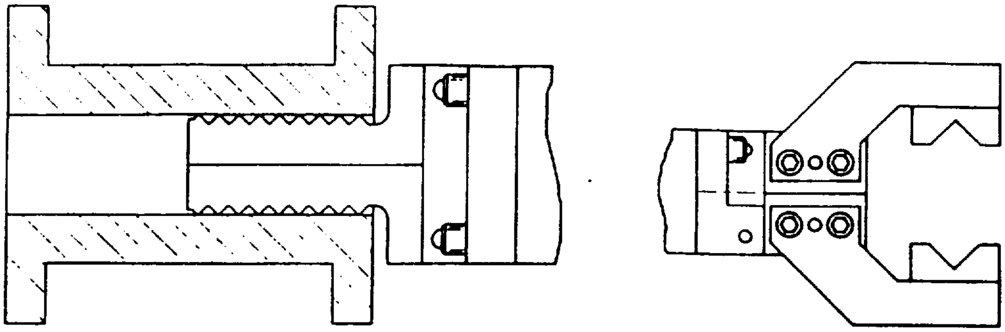


(a) Two-Jaw Angular Gripper (b) Two-Jaw Parallel Gripper

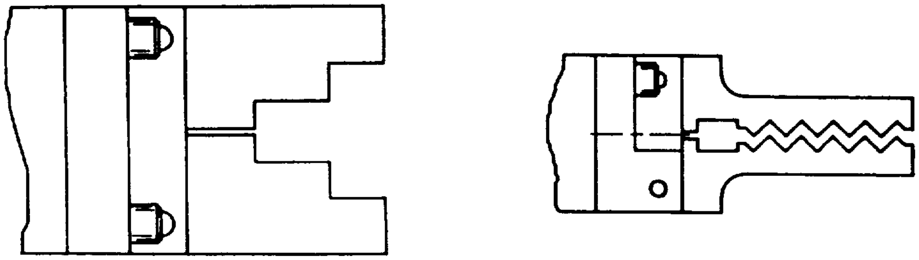


(c) Three-Jaw Angular Gripper (d) Three-Jaw Parallel Gripper

Figure 3.2 Commercial Grippers - Source: Robotic Accessories, 6555 S. State Rt. 202, Tipp City, Ohio 45371



(a) General Purpose V-Jaws (b) I.D. Gripping Jaws



(c) Stepped Jaws (d) Serrated & Carburized Jaws

Figure 3.3 Examples of Specialized Gripper Jaws - Source: Compact Air Products, Inc., P.O. Box 499, Westminster, SC 29693-0499

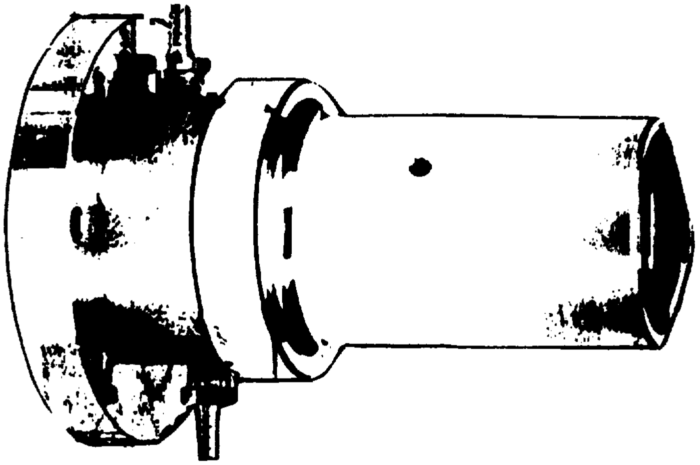


Figure 3.4 Collat Jaws for Precision O.D. Gripping - Source: Robotics Accessories, 6555 S. State Route 202, Tipp City, OH 45371

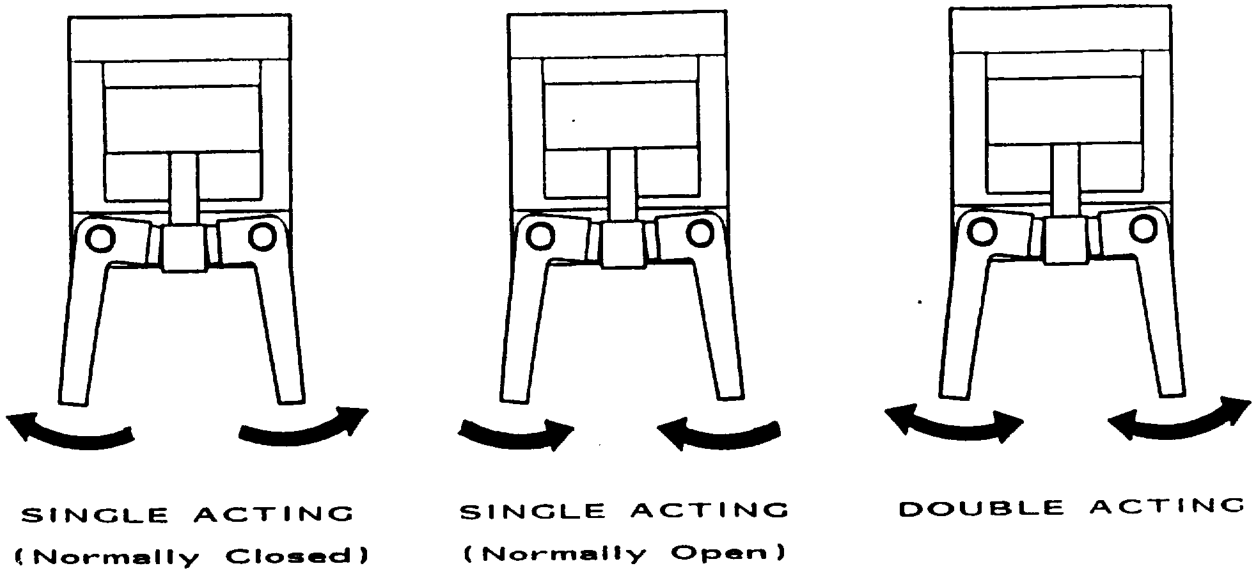

SINGLE ACTING
(Normally Closed)
SINGLE ACTING
(Normally Open)
DOUBLE ACTING

Figure 3.5 Schematic of Single-Acting Vs. Double-Acting Grippers

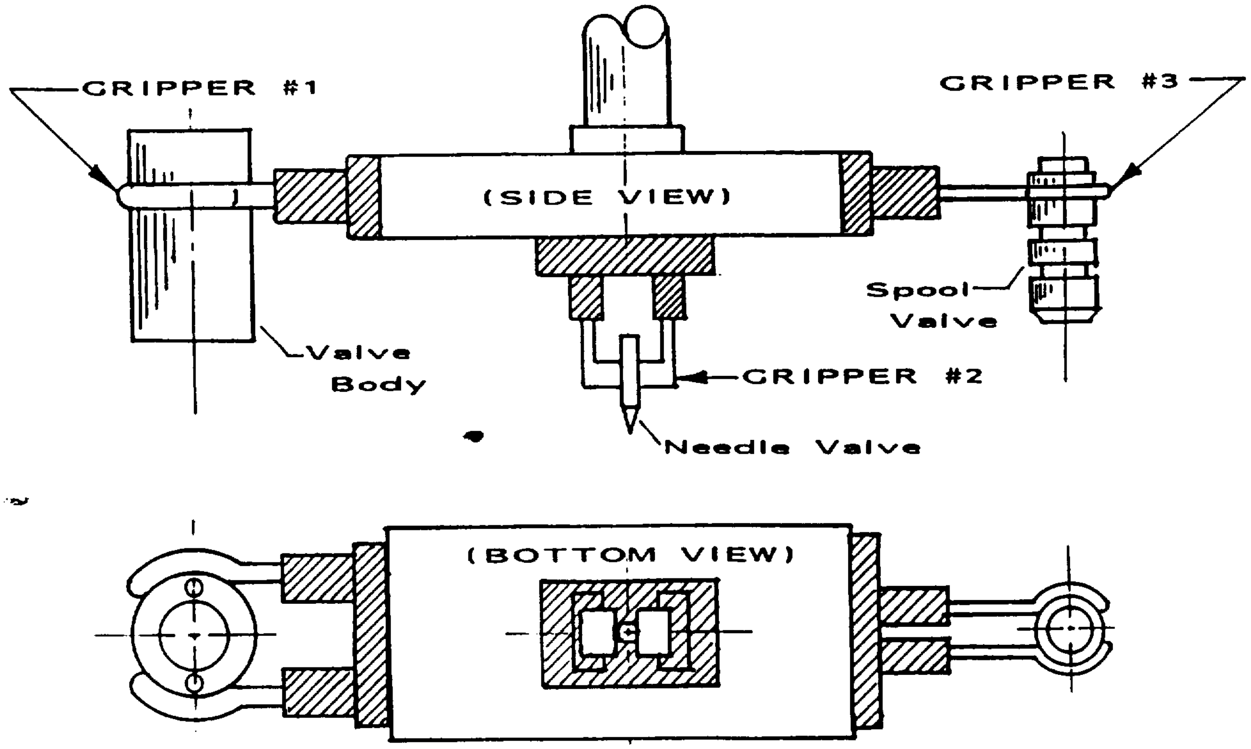
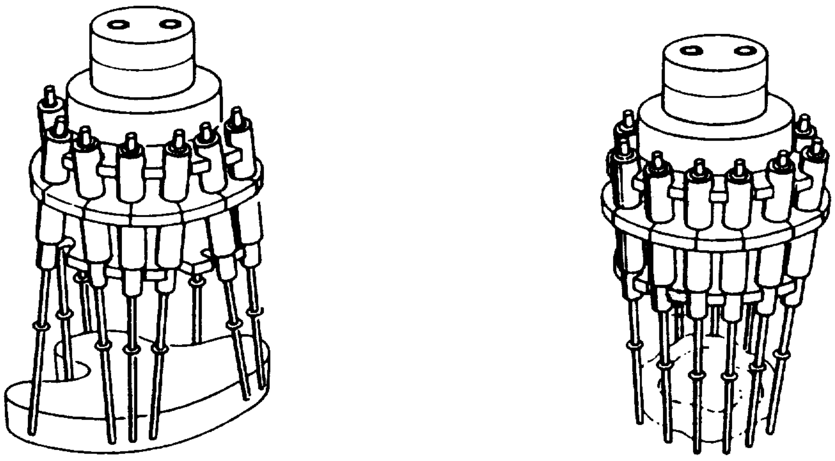
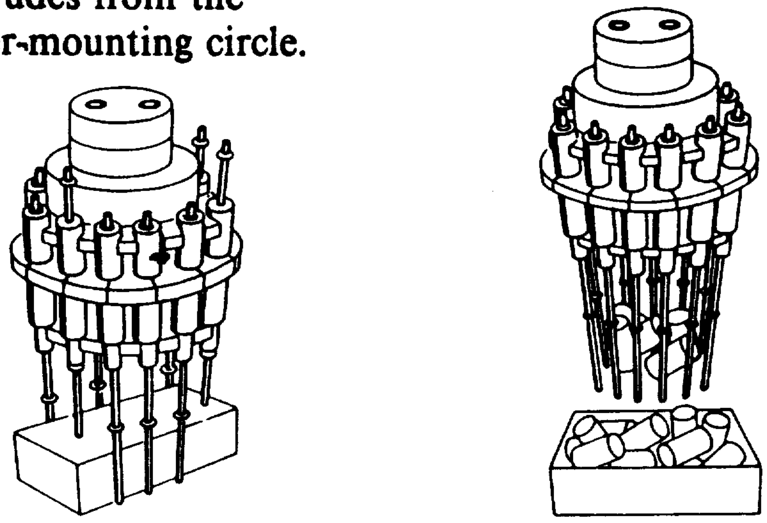

GRIPPER #1
GRIPPER #3
(SIDE VIEW)
Spool Valve
Valve Body
GRIPPER #2
Needle Valve
(BOTTOM VIEW)

Figure 3.6 Multitask End-Effector Configured With More Than One Set Of Grippers



1. Workpiece of an intricate shape.

2. Soft workpiece.



3. Workpiece that partly protrudes from the finger-mounting circle.

4. Loose workpieces.

Figure 3.7 Typical Applications of the NKE Flexible Gripper
Source: Jergens NKE, Special
Products Group, Division of Jergens, Inc.,
19520 Nottingham Rd., Cleveland, OH 44110

3.2 Product Review: Dexterous Robotic Hands

Introduction - The review of dexterous robotic hands indicates that, while efforts reported in the literature in the development of robotic prosthetic devices date back to the late sixties, only in recent years have very great strides been taken toward the development of the current generation of dexterous robotic devices. The early work in robotic finger development focused on the execution of simple grasping motion for non-anthropomorphic hand designs, with a single degree of freedom.

These earlier designs though simple and mechanically durable, had only a modicum of dexterity and were limited in their application, performance and productivity. They could securely grasp objects by the use of mechanical force control capabilities resident in operator arm or active joints of a robotic manipulator; they also utilized a variety of dedicated and special purpose grippers with different finger shapes and actuation mechanisms for grasping objects.

The period between the late 60's through the 70's witnessed the development of grippers and anthropomorphic prosthetic devices, which have enabled both simple and dexterous grasping of objects. In the succeeding period, the need to broaden the range of grasping motions and the dexterity of robots has led to the development of computer controlled dexterous articulated robotic hands.

The more recently developed dexterous hands incorporate anthropomorphic hand design features, and perform dexterous motions with skills and speeds that approach those of the human operator. These hands offer the advantage of being able to impose motions on grasped objects under either programmable control or more ideally, teleoperated robotic control. In general dexterous robotic devices are more flexible, reliable and deliver greater precision when operated under a variety of conditions employing computerized control.

Some factors that have driven the current progress in dexterous robotic devices include the drive toward a better understanding of man-machine interactions, mounting safety concerns, the need to extend the range of human operations to unstructured or hostile environments, and a greater desire to duplicate human hand dexterity in robotic hand designs.

In the sections that follow over twenty five such dexterous hands are reviewed.

3.2.1 Sarcos/Univ Of Utah Dexterous Robotic Hand

Sarcos Inc., Salt Lake City, and the University of Utah's Center for Engineering Design have developed a high performance anthropomorphic (human like) manipulator (Figure 3.8) that can duplicate most of the efforts performed by a human arm and hand [3.1]. It has ten degrees of freedom (DOF), including a three-DOF end-effector designed to handle standard tools and other objects with human-like dexterity. The dexterous arm has a hand with a thumb and two fingers, wrist, elbow and shoulder. The arm is powered by high pressure (3000 psi) hydraulic devices. According to Jacobsen [3.1], the pressure range of 3000 psi gives the best power-to-weight ratio for a high performance robot. Jacobsen [3.1] submits that a key to industry grade performance is high power densities which are obtained by use of high pressure hydraulic systems.

According to Jacobs‡ ‡‼àèïĩò¥ulics provides the best combination of stiffness and speed. To overcome the problems of leaks and dirt accompanying typical hydraulic systems, leak-free redundant sealing systems were used. Hydraulic fluid lines instead of hoses were used in the design, coupled with the use of redundant seals. The fluid lines are installed at leak sensitive locations. At these potential leak locations, fluid return values are installed and connected to a drain passage that feed the leaks to the return lines. Drips or leaks that travel past the return line seals get caught and evacuated before reaching the surroundings. This exercise of "sensible engineering" in surmounting a major conventional hydraulic system drawback, allows the Sarcos hand and arm to work in environments previously off-limits to hydraulic devices. A force reflecting hand master which has 10 degrees of freedom controls the dexterous hand.

3.2.2 Odetics Hand

Odetics Inc. [3.2] under a contract administered by the Jet Propulsion Laboratory in Pasadena, California, has developed a dexterous robotic arm capable of articulating a dexterous end- effector (Figure 3.9). The versatile device is lightweight (150 lbs) and capable of lifting 50 pounds of load under earth gravity. The high strength arm, fifty five inches long and 6.5 inches in diameter at the shoulders features seven (7) degrees of freedom, the same number possessed by the human arm. Though the dexterous arm was originally designed to lift large assembly units during space station construction, it is now considered a viable option for customization to Earth applications such as the transfer of solid or radioactive waste.

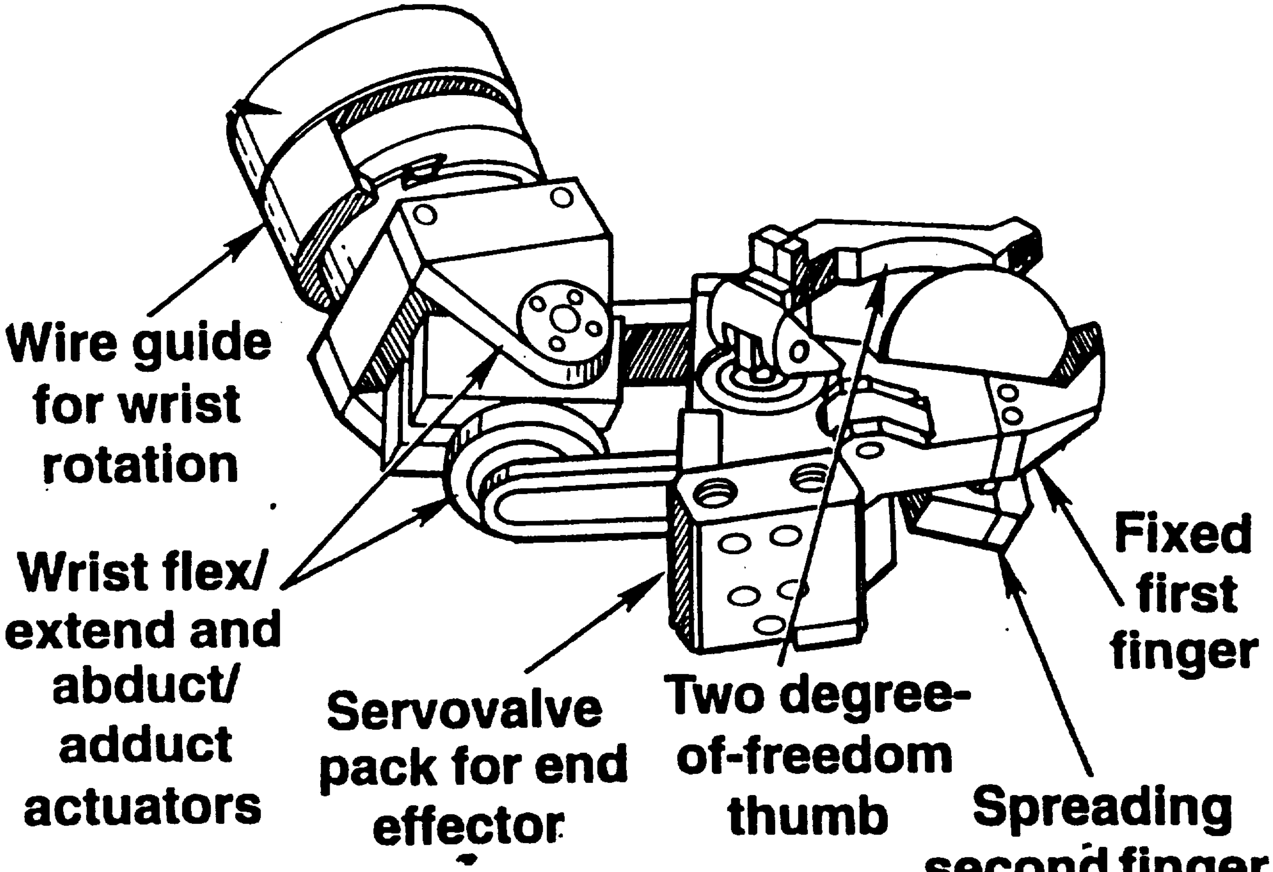

Wire guide for wrist rotation
Wrist flex/ extend and abduct/ adduct actuators
Servovalve pack for end effector
Two degree-of-freedom thumb
Fixed first finger
Spreading second finger

Figure 3.8 Sarcos/Univ of Utah Dexterous Robotic Hand

The Odetics manipulator solves typical mechanical and control problems. To avoid the problem of backlash which generates considerable instability in a control system, each arm employs two brushless dc motors doubling the drive system that powers two-stage planetary gearboxes. One motor serves as a prime mover while the other provides an opposite bias torque cancelling backlash. This arrangement provides the additional design advantages of fault tolerance. The probability of loss of arm functionality is greatly diminished by the dual motor powering arrangement. Should one motor fail, the other can operate the joint, although with decreased effectiveness. Sensors provide absolute positioning data and therefore eliminate the need to "zero" the arm during the startup of the system. Complete disassembly of the arm for assembly or transport can be accomplished in less than ten minutes.

3.2.3 Omni-Hand (Ross-Heim)

Ross-Heim Designs Corporation of Minneapolis, Minnesota, has completed the development of the three digit Omni-Hand [3.3], using Minnac^{TM} linear actuators. The hand (Figure 3.10) was developed for NASA, and claims to be the first direct-drive rugged robotic hand with humanlike motion. Omni-Hand is ready for commercial, educational, research and development, as well as robotic applications. The Minnac^{TM} is the first miniature electric linear actuator to combine high power and servo control. Minnac^{TM} is designed for a wide range of positioning needs including packaging, automated manufacturing, and aerospace. Ross-Heim Corporation is also the developer of the singularity-free positioning technology.

3.2.4 The Digits Finger

Orin et al. [3.4] of the Ohio State University have developed the DIGITS robotic system (Figure 3.11) illustrated as Dexterous Integrated Grasping with Intrinsic Tactile Sensing (DIGITS) system having six-axis force sensing in each finger tip. The system which is finger-like, has been designed for the study of manipulation phase finger movements and power grasps.

This system is a twelve independent degree of freedom device that is similar to an anthropomorphic hand. Its minimal packaging constraints allow high performance drive configurations.

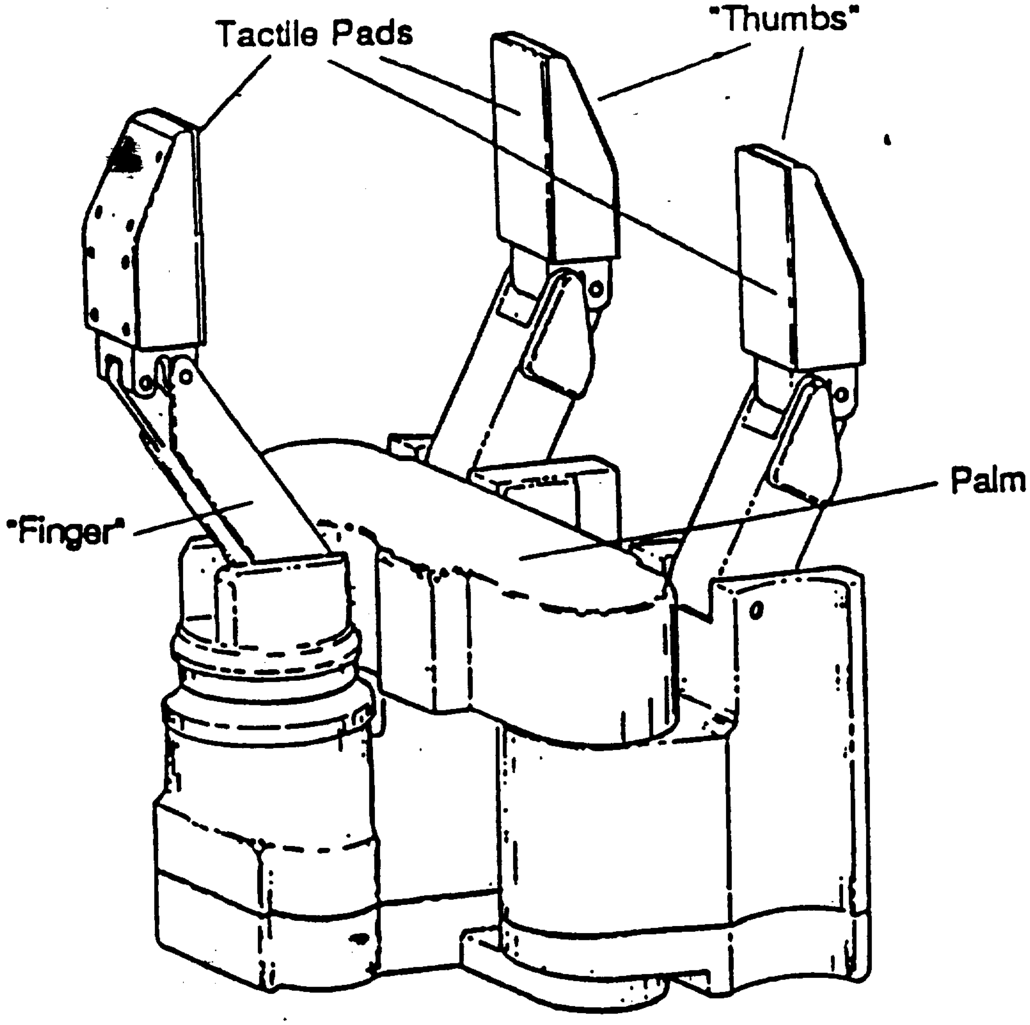

Tactile Pads
"Thumbs"
Palm
"Finger"

Figure 3.9 Odetics Hand

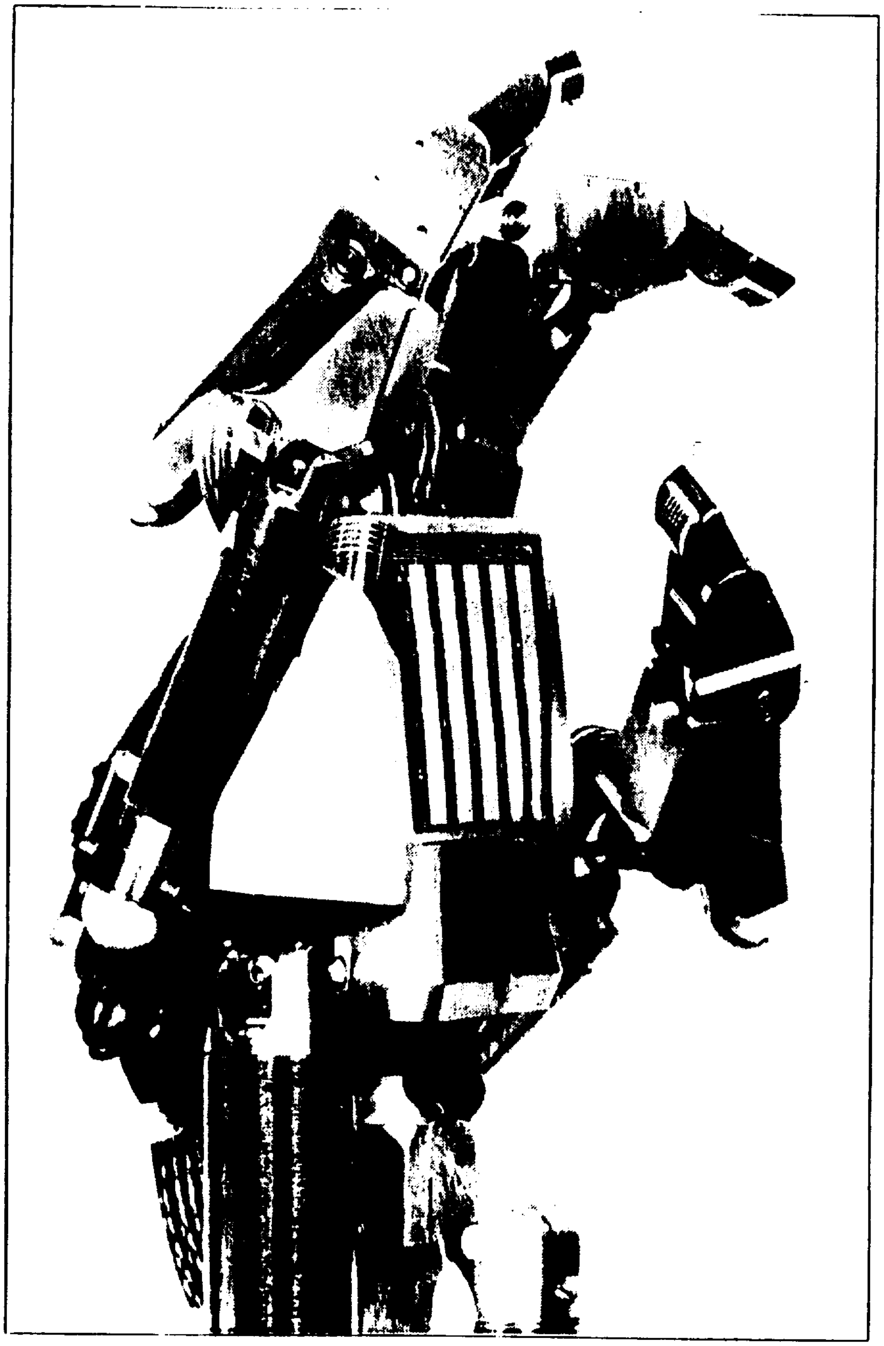


Figure 3.10 Omni Hand (Ross-Heim)

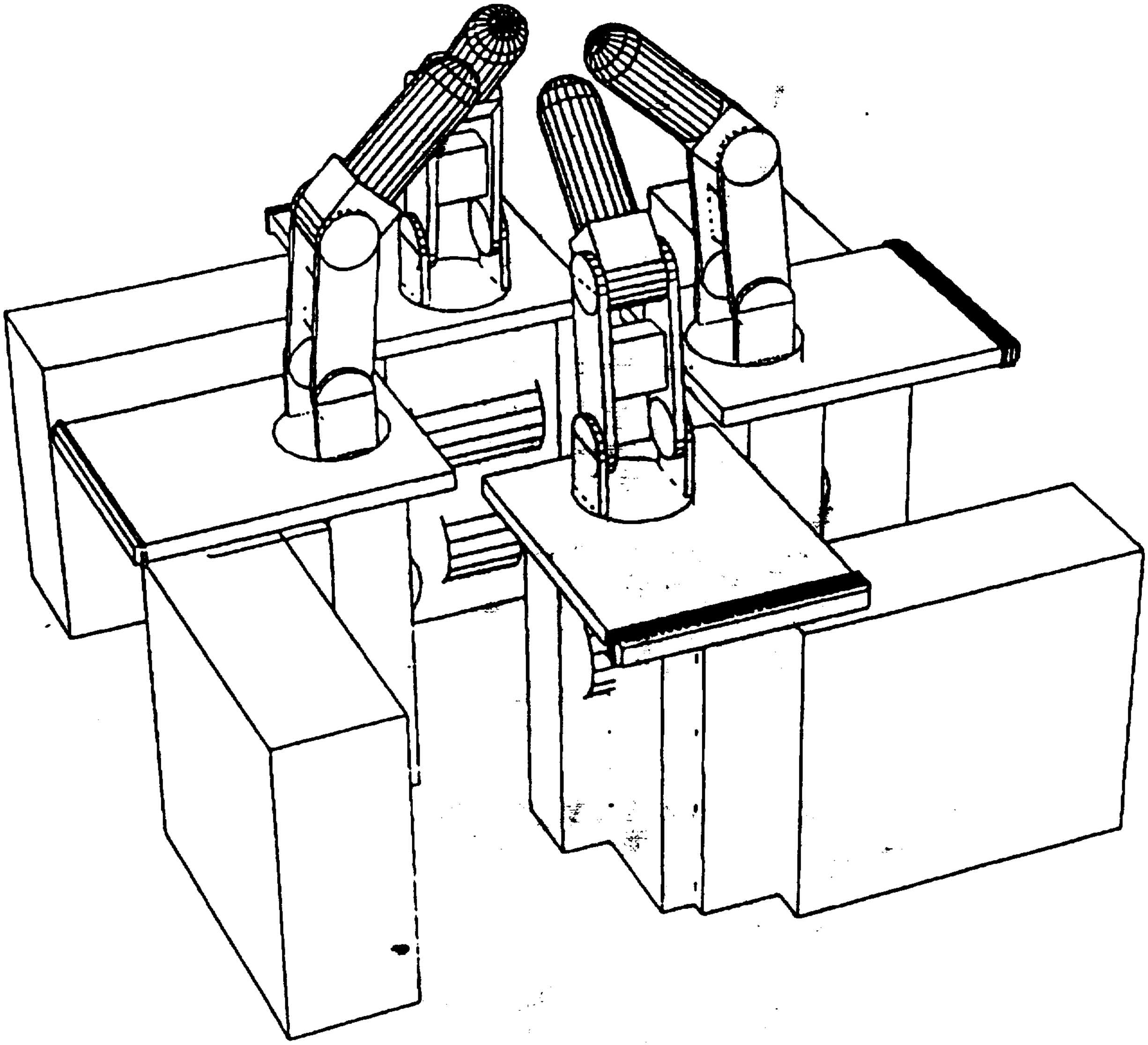


Figure 3.11 The Digits Finger Robotic Hand

Performance Characteristics - Performance characteristics of the DIGITS system allow it to grasp objects with weights up to 5 lbs per digit, while it can sustain 4 lbs continuous force level at the fingertip when fully extended. Fingertip velocities of fifty inches per second (50 in/sec) have been secured in operating the DIGITS system. The system weighs approximately 30 lbs, has a maximum frequency of 25 Hz with an amplitude of 1".

A "finger" of the DIGITS system is similar to one of the Stanford/JPL fingers. Force information can be used to locate effective points of contact on the DIGITS fingertip. The modular design of the finger allows for different combinations of finger arrangements, while simultaneously ensuring few packaging constraints, leading to high performance for a given finger arrangement.

The DIGITS finger is electrically powered by a brushless DC servo system with built in position and force feedback control. Each finger tip has six axes force sensing capability, through the use of machined aluminum with bonded strain gauges.

Power is transmitted using a brushless DC motor with a two stage (15:1) belt drive. The drive is coupled via grooved pulleys to the brushless DC drive motor.

The control system for the DIGITS finger incorporates a custom real time operating system referred to as GEM, which is a state of the art control of interface electronics system, with multi-processor coordination using the SUN workstation. The programming environment for the DIGITS system is the Pascal language.

3.2.5 Harvard Hand

The Harvard University Robotics Laboratory [3.5, 3.6] researchers have developed a linked, planar, two finger, one thumb robotic hand (Figure 3.12). The hand configuration, which incorporates the capability of tactile sensing and feedback control under teleoperated and autonomous modes, was developed using the ECLIPSE MV/10000 supermini computer with color graphics terminal, and 16 additional display terminals. The hand's design gives it the ability to adapt to objects of differing shapes. The configuration of the Harvard University hand is similar to the design of the NASA/JPL two thumbed hand. While the NASA/JPL hand incorporates a left and a right thumb and a middle finger, the Harvard University hand incorporates two fingers and a thumb in its construction.

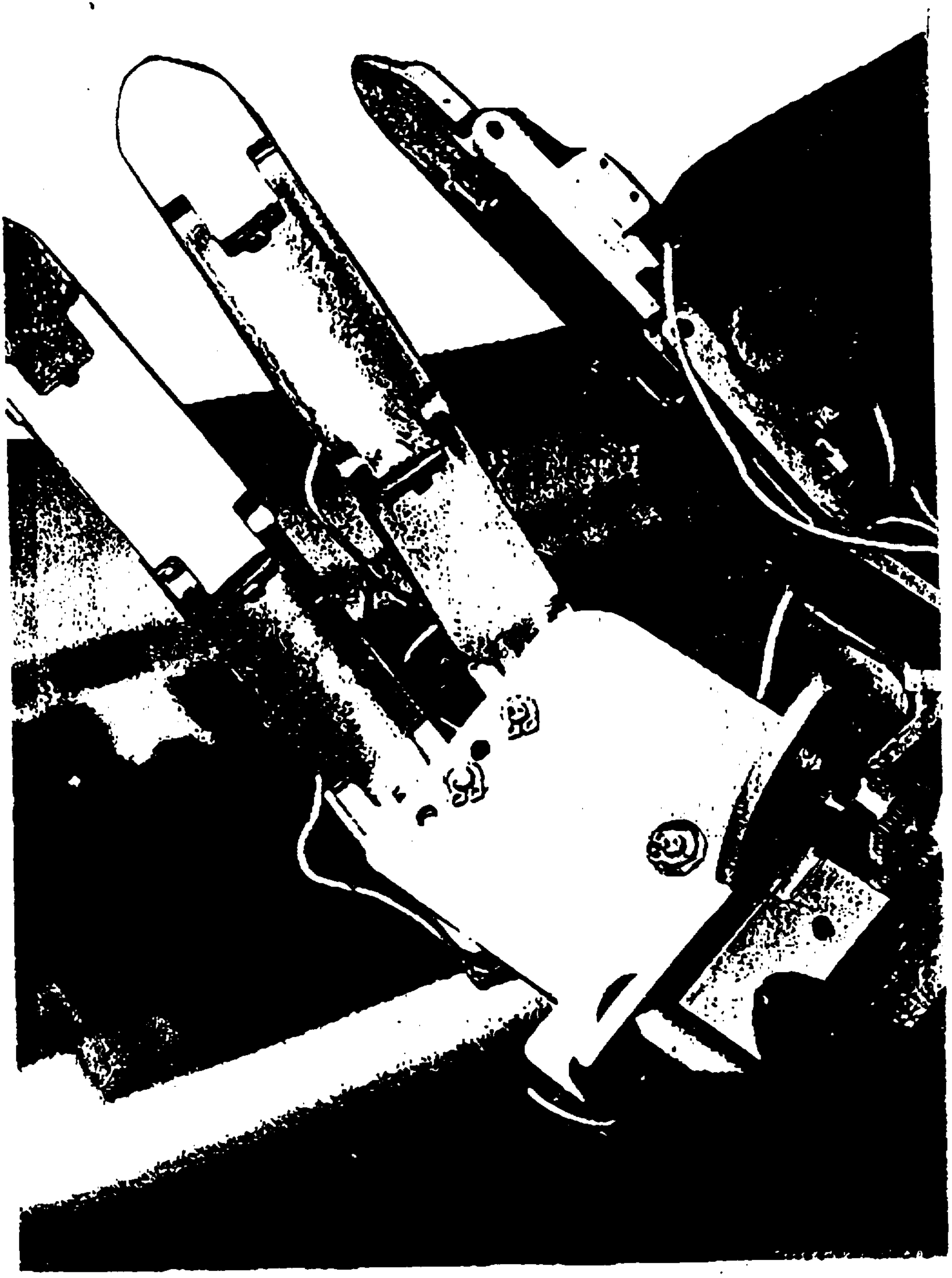


Figure 3.12 Harvard Hand

3.2.6 Ames Research Center Prehensor

A mimic mechanical prehensor [3.7] has been developed to protect the human operator from proximal but enclosed and potentially dangerous environments. The Ames Research Center in Moffett Field, California has developed an operator powered mechanical hand (Figure 3.13) that offers protection, leveraged dexterity and proximity. The mechanical prehensor which has a ring finger, an index finger and a thumb, replicates the movement of an operator's hand and fingers just a few centimeters from the hand and workpiece. Through the intervention of a protective shroud that encloses the operator's hand, the prehensor enables the operator to grasp, hold, and manipulate nearby objects in hostile or hazardous environments. The shroud is made of a rigid, gas impermeable material such as aluminum or molded fiberglass. It is joined to the supporting frame by welding, bonding or other means that ensures an airtight seal. When an operator moves a finger, the movement is translated by mechanical linkages into a similar movement of the corresponding part of the mechanical prehensor. The prehensor obviates the use of electric motors or electronic circuits since the operator moves the prehensor through mechanical linkages.

3.2.7 Penn Hand (University of Pennsylvania Hand)

The Penn Hand, Version II, (Figure 3.14) developed by Ulrich et. al. [3.8] of the University of Pennsylvania is a three-fingered, two-jointed hand that is supported by the substructure of a base. The Penn hand, which is approximately 25% larger than the human hand, weighs about 1.5 kg, can exert fingertip forces of 50 N, and can move its finger joints through their complete range in 1/2 second. With three-to-five degrees of freedom depending on the grasping task, its design enables it to have the versatility of the more complex hands in addition to the robustness, economy and ease of control characteristics of simple grippers. Two of the three finger bases of the Penn hand are moved by actuators synchronously around a central palm. Similarities exist between the functioning of the Penn Hand and the human hand. The movement of the last two joints of the human finger are coupled together, the two joints of the Penn Hand follow a similar relationship. Since it is possible but rarely necessary to move each finger of the human hand individually, the Penn Hand fingers as well as the individual joints are moved cooperatively and the functions of the five human fingers are essentially consolidated into three fingers

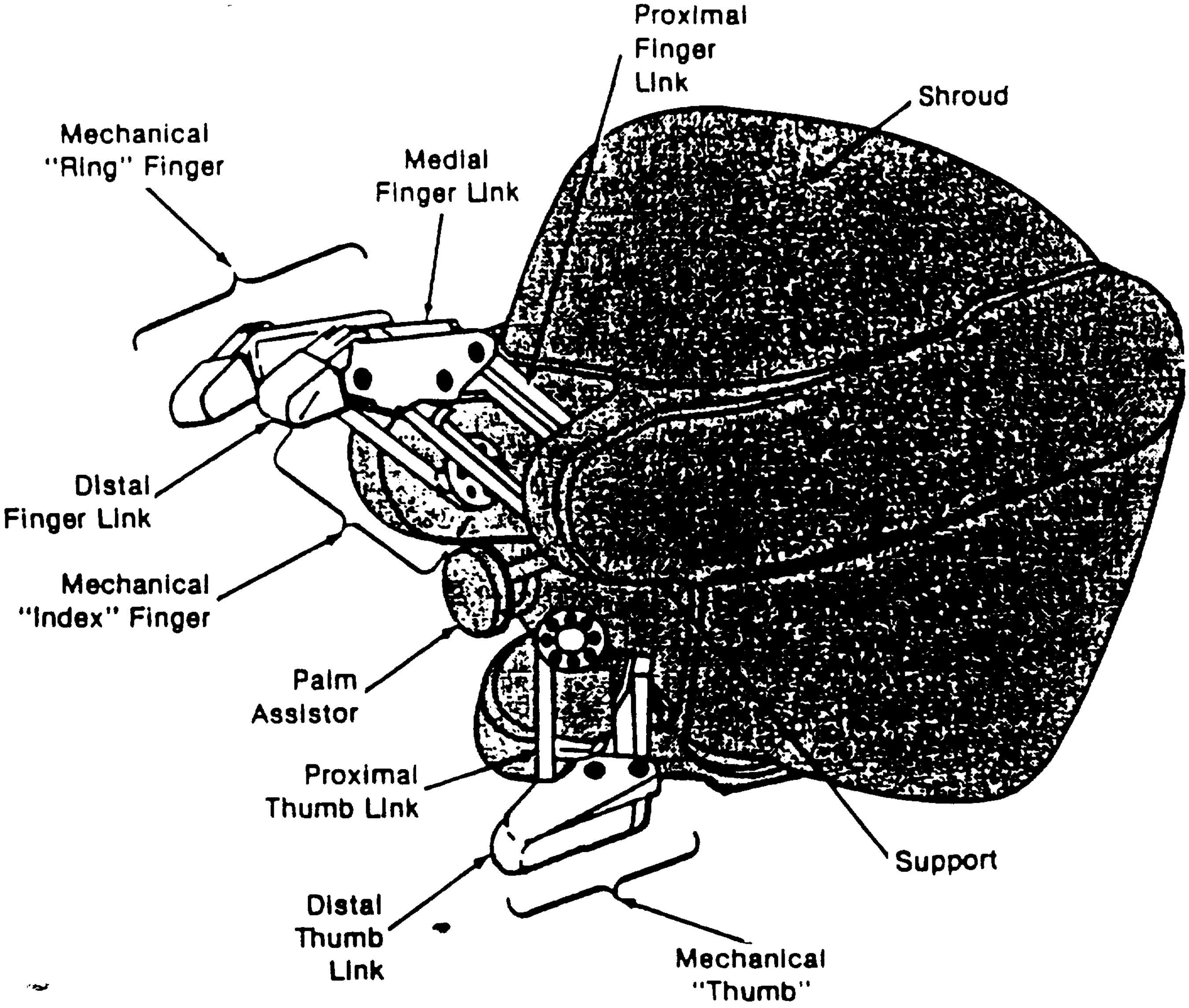

Proximal
Finger
Link
Shroud
Mechanical
"Ring" Finger
Medial
Finger Link
Distal
Finger Link
Mechanical
"Index" Finger
Palm
Assistor
Proximal
Thumb Link
Support
Distal
Thumb
Link
Mechanical
"Thumb"

Figure 3.13 Ames Research Center Prehensor

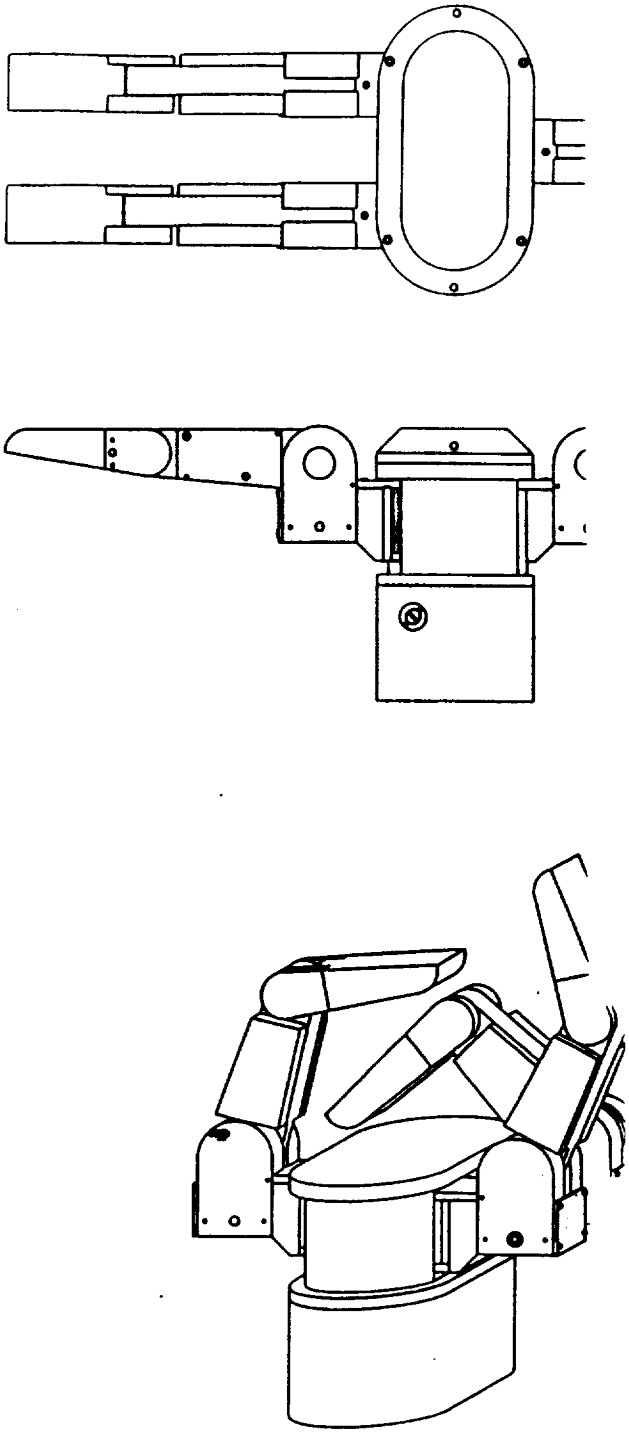


Figure 3.14 Penn Han

Torque sensing in the Penn Hand is accomplished using strain gauges which also assist in the calculation of contact forces under closed loop control. The early teleoperated version of the Penn hand used standard utility tools like screwdrivers and wrenches to partially disassemble a small internal combustion engine.

3.2.8 Anthrobot-2

Mike Ali and Charles Engler, Jr. both researchers at the NASA Goddard Space Flight Center have developed the Anthrobot-2 hand (Figure 3.15) which is a tendon-driven, five-fingered, fully functional robot hand that can interface with commercial exoskeletal gloves [3.9]. It consists of four fingers and a thumb, each with four degrees of freedom. A total of 20 degrees of freedom and 16 controllable degrees define the hand configuration which weighs 1.75 lb. Each finger has four joints as in the human hand, two at the knuckle for lateral and vertical motion, one between the proximal and middle finger segments, and one between the middle and distal finger segments. A key area in the design is the palm which has a curve similar to the human hand where the finger meets the palm. The dimensions of the hand not including the actuator housing and wrists are 7.5" (l), 3.5" (w) and 1.1" (h) maximum thickness. The mechanical structure is composed of 6061-T6 aluminum.

The Anthrobot-2 represents an improvement over its predecessor, the Anthrobot-1, developed by Charles Engler in 1988 for a master's thesis at Lehigh University. The current improved version of the hand is lighter, smaller, easier to assemble, and more anatomically congruent than the original hand. The finger and thumb joints are actuated by Futuba Servomotors via a system of tendons modeled after those in the human hand. The servomotor package includes a motor, gear train, a potentiometer, and servo electronics. The servomotors actuate the fingers via a system of tendons modeled after those of the human hand. A wrist servomotor is currently under development. Incremental encoders are used for feedback control. Anthrobot-2 is designed to fit on the end of a variety of industrial manipulators or robots.

Servomotor control by open loop is implemented using IBM PC compatible computers. Pulse generation using the PC-CTR-20 pulse generator board creates the pulses needed to command the Futaba servomotors. A 20-MHz 80286 microprocessor is adequate for the current open loop system. Development work continues leading to future close loop control with a bandwidth of 5 to 10 Hz; the current computer microprocessor specification will be adequate.

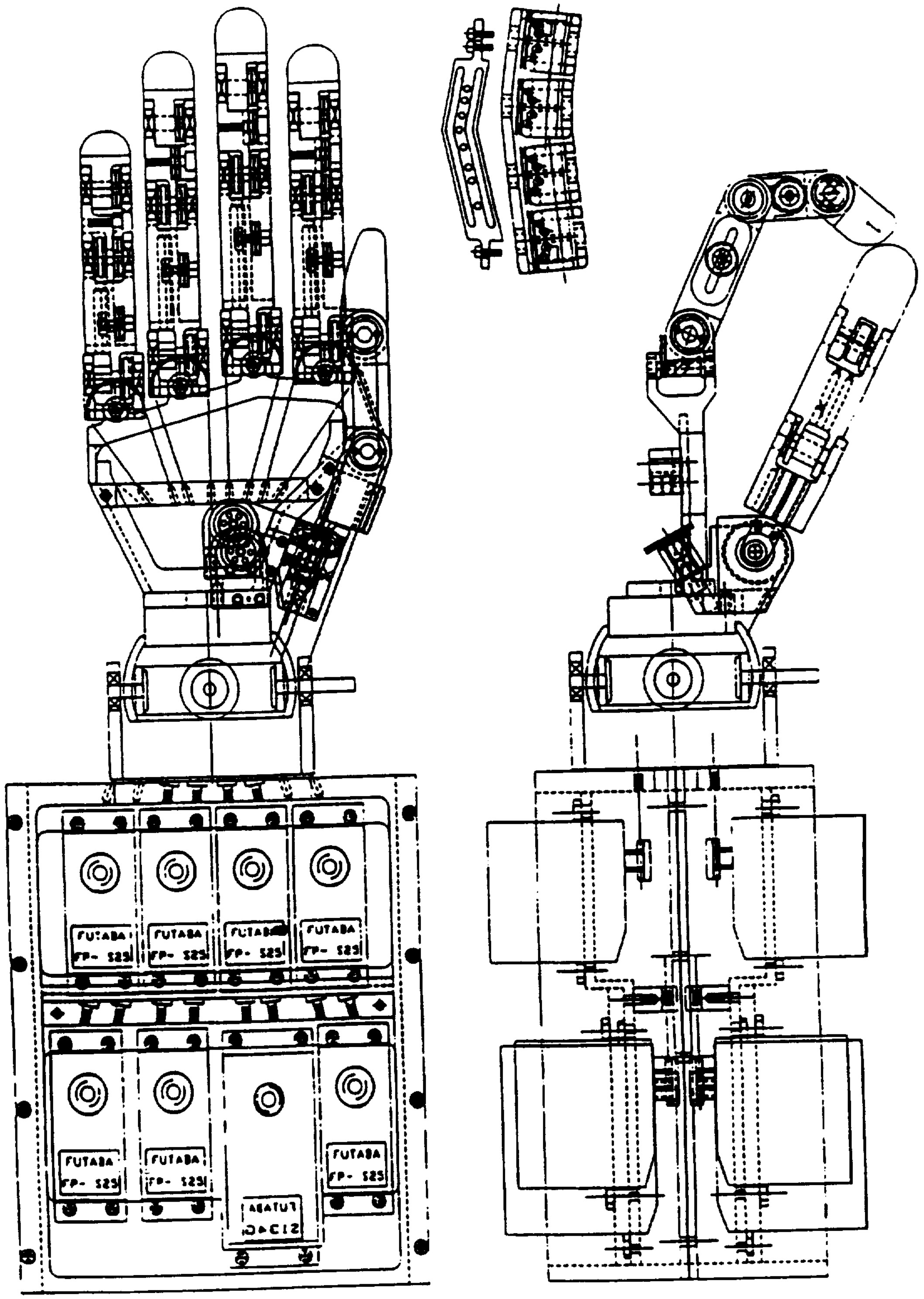

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Figure 3.15 Anthrobot-2

The software interface consists of two modules written in the C programming language. While the first module initializes the counter board, the second module controls the width of the generated pulses by writing the appropriate register on the counter board. Optional modules interface the Anthrobot-2 using the Nintendo Power Glove and the Exos dexterous hand master. These modules allow the user to operate the hand in master slave mode.

The Anthrobot-2 has the same range of motion as the human hand. It can exert tip forces of 2.2 lb and 6.3 lb for the finger and thumb respectively. Planned enhancements to the Anthrobot-2 include tactile sensing capabilities to enhance its broad range of capabilities.

3.2.9 Robot Digits

Robot digits [3.15] which is a refinement of the Anthrobot-2, has been jointly developed by Mike Ali, of the Rensselaer Polytechnic Institute in New York and Charles Engler of the Goddard Space Flight Center. The device is a five-fingered dexterous robot hand that functions as a human hand. The hand represents a continuation of the work of refining the Anthrobot-2 developed at the Goddard Space Flight Center [3.9]. The operator moves each digit of the dexterous hand digits through a control glove worn on the operator's hand. Further development of this hand which is intended for commercial use is in progress. Enhancements include the development of a tactile sensor and a feedback system for incorporation into the hand's performance.

3.2.10 Scientific Research Associates Robot Hand

Scientific Research Associates [3.16] has developed an intelligent flexible robotic system which has the potential of cleaning up toxic wastes on Earth, building structures in orbit, and performing repetitive manufacturing tasks. Other areas of application include space commercialization, mining, and exploration. The robot combines the latest in robotics, flexible structure design, 3-D cooperating robot arm motion control and machine vision advances. The dexterous robot incorporates 18 degrees of freedom, a moveable head, two CCD cameras for producing stereoscopic real-time vision, two cooperatively dexterous arms, and expandable shoulders, all of which enables the arm to perform complex mechanical tasks. The robot arm can wield various tools, and perform precise functions such as microelectronic chips replacement and circuit board substitution. Using artificial intelligence techniques, the robot can learn from its mistakes by storing data from previous tasks. For ease of repair and upgrade enhancements, the robot has a modular design, the robot's many subcomponents work in harmony under the supervision of a host computer via a local area network (LAN) control.

3.2.11 MIT-Salisbury Hand

The MIT-Salisbury Hand (Figure 3.16), developed at the Massachusetts Institute of Technology [3.10, 3.11], is a multidevice integrated robotic system that can perform such tasks as manipulation and sensing. The hand incorporates finger tip, wrist force and torque sensors. It also incorporates spatially resolved tactile array. Flexibility in robotic operation results from sensor fusion and intelligence specification. The added advantage of fault tolerance is obtained.

The MIT Salisbury hand sensors have all been integrated into an expert system [3.12] for object recognition and grasp generation to demonstrate autonomous grasping of arbitrarily unknown objects. The expert system has been developed to reason about objects and manipulate them after input data from the visual and tactile sensors are fed into it.

3.2.12 Leuven (Belgium) Hands

The 3-D Leuven (Belgium) hand (Figure 3.17a) developed by the Katholieke Universitiet in Leuven, Belgium [3.13] is a multifingered device that can handle various shapes of objects and manipulate these in six degrees of freedom. The flexibility of the Leuven hand makes it possible to eliminate human interaction in hazardous and unstructured environments. The hand has three fingers and nine degrees of freedom. Every finger has three driving motors and three force sensors in the fingertip. The finger tip sensors have a minimum resolution of 0.2 N. A 16-bit microprocessor with a numerical coprocessor is used for implementing the complex control task at three levels: finger control, hand control and task control. To achieve a higher power/volume ratio, a tendon type actuation was chosen powered by an electrically driven linear actuator. By using data from several tactile sensors, the hand should be able to perform multiple kinds of grasping, such as three finger grasps and palmar grasp.

In addition, a 2-D hand [3.14] has also been developed consisting of two fingers driven by seven tendons (Figure 2.17b). The hand utilizes embedded tactile sensors on every phalanx of the device. The local curvature and position of the object is determined without apriori knowledge of the object. The version II hand is controlled by a transporter whose parallel processor system permits flexible task-to-processor assignment for the various control tasks of the hand such as motor control, sensor data acquisition, task interpretation and user interface.

Further work on the hand has involved the applicability of Shape Memory Alloys (SMAs) for miniature robotic hand actuation. A miniature actuator prototype using the NiTi alloy, a low resistance alloy, has been designed for generating a torque of 75 N-mm. It consists of a wire with a rectangular section which is driving a pulley system. The resistive heating and oil cooling of the SMA are used to obtain the necessary power transmission. Data for the Temperature-Stress-Strain behavior of the actuator was obtained using specially constructed equipment.

3.2.13 Equalizer Manipulator

Erie Press System [3.17] developed the "Equalizer" a seven degree of freedom high precision and payload materials handling system. The equalizer has an end-effector that is an extension of the operator's arm. Spatially proportional arm controls along with operator feedback provide the equalizer with the dexterity of the operator's hand. A single arm of the operator can actually feel what the equalizer is doing and respond accordingly. The other hand of the operator is free to operate other equipment through 24 interface circuits.

Advantages of the Equalizer, which can handle loads varying in size from 500 lbs to 6000 lbs, include: quality enhancement through uniform handling of raw and work-in-progress materials for manufacturing processes; improved productivity through handling of heavier payloads; enhanced safety resulting from the efficient processing of heavier loads by the Equalizer; and, drastic fatigue reduction.

3.2.14 U. of California-Irvine/McCarthy Hand

Performance Characteristics - Leaver and McCarthy et al. [3.18, 3.19] have designed a lightweight dexterous robot finger (Figure 3.18) to aid in tactile sensing research. The device has two degrees of freedom for the finger which is tendon actuated.

The UCI finger is a three link planar digit with the joints actuated through cables by two motors. The entire finger assembly weighs approximately 12 ounces, and can carry a payload of 5-17 ounces depending on the cable routing configuration. The finger digits are mounted on a 2.5 x 2.5 square inch base that houses the two actuators.

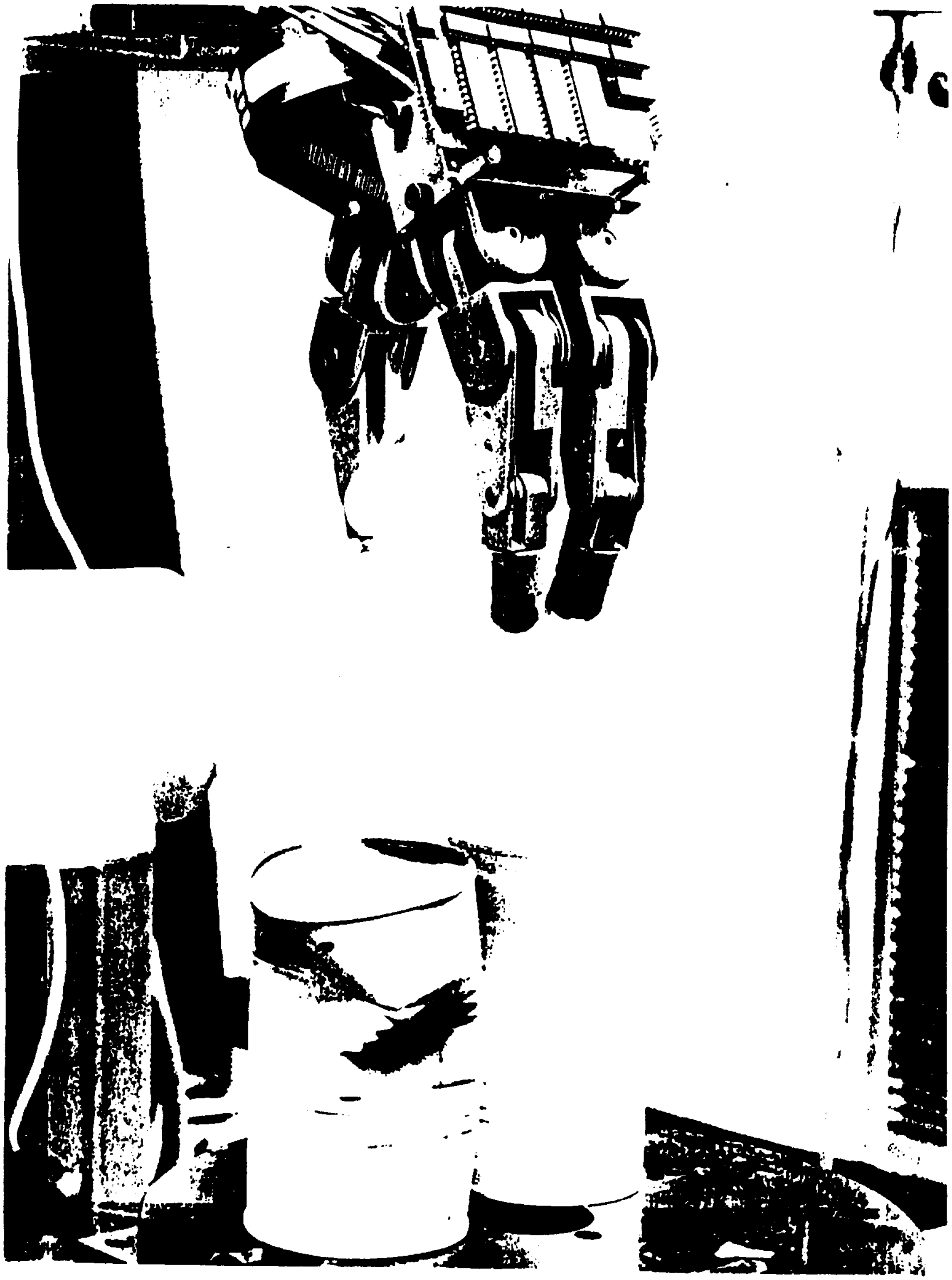
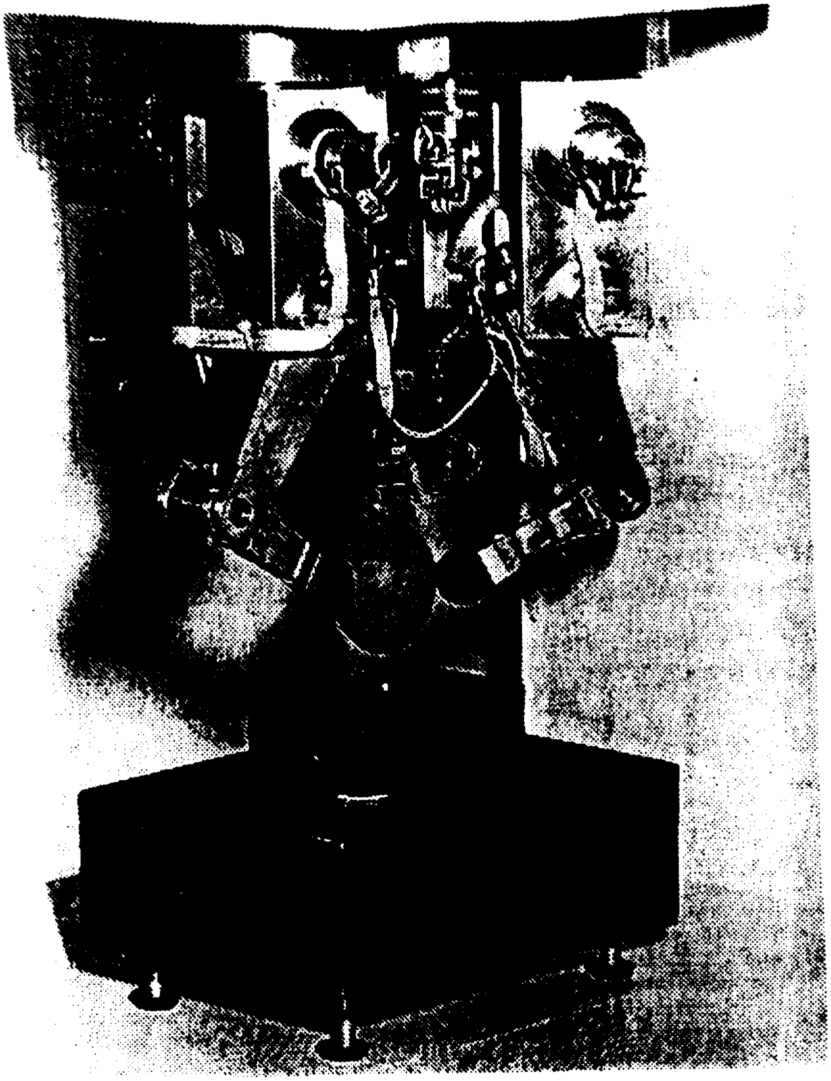
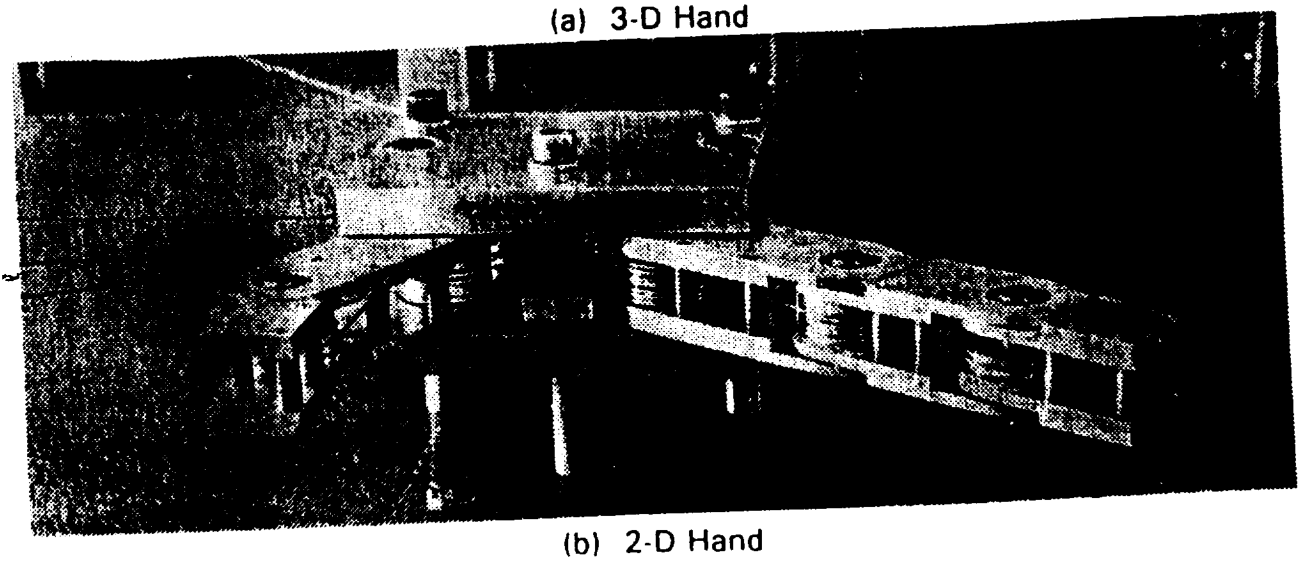


Figure 3.16 MIT Salisbury Hand



(a) 3-D Hand



(b) 2-D Hand

Figure 3.17 Leuven (Belgium) Hands

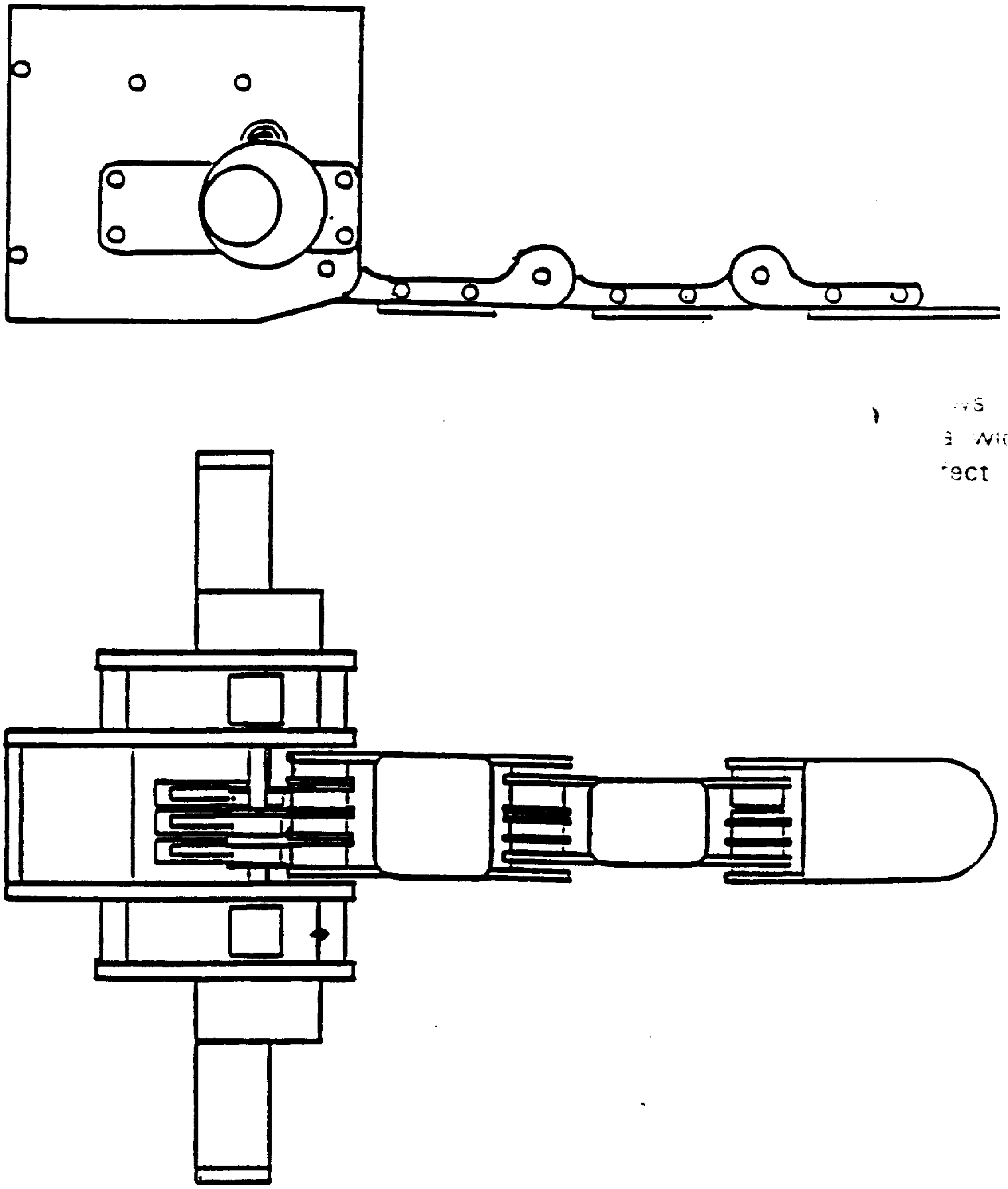


Figure 3.18 University of California-Irvin/McCarth Finger

The tendon actuated finger is 6 inches long and 0.75 inch wide. Stranded steel tendon cables with Teflon-coated covering are routed over 0.44 inch diameter pulleys which are supported on precision ball bearings to reduce the effect of friction.

Actuators - The actuator for the hand is a 12 Volt DC motor with a 172:1 speed reducer, that produces stall torques of about 60 ounce-inches. To achieve effective actuation, an analog tension control loop is provided to control the operation of the motor speed reducer system. This scheme has been used by Salisbury and Craig et al. [3.38].

The three joints are actuated by two motors via cables. This finger development was governed by two design goals, namely: a lightweight finger; that consumes the least amount of power. To achieve the low power consumption goal, a high speed low torque motor with a 172:1 speed reducer is used for actuation. The finger weight reduction was achieved by the use of two motors to actuate the three joints of the finger. The use of large speed reducers enabled the minimization of the weight and power consumption of the motors.

Position & Force Sensing - The UCI finger, which has three actuator cables routed over pulleys, has strain gauges mounted to measure cable tension. The strain in each cable is converted to a voltage signal for subsequent processing on a strain gauge interface board, which is also mounted on the base of the finger.

Position and force feedback information is provided through Hall effect sensors and strain gauge sensors on each cable. Position sensing is effected using a magnet and a Hall effect integrated circuit, which are mounted in each of three joints to measure the relative position of movement. The Hall effect sensor interface board is mounted in the base of the finger, and provides a regulated voltage source to the Hall effect sensor.

Since the relationship between the voltage applied to the motor and the output torque of the speed reducer may not be predictable or linear, because of the presence of friction and backlash in the speed reducer, an analog circuit was designed to measure the torque output of the actuator by sensing the tension in the cable drive and using it to control the current to the motor.

The bandwidth [illegible] the joint tension controller system was 22 Hz. This is comparable to the bandwidth of the PUMA manipulator torque control system reported by Pfeffer et al. [3.50] in 1986, which was over 20 Hz. A position control system implemented for the UCI hand has a bandwidth of approximately 5 Hz., which compares well to that of the second joint of the Stanford/JPL hand reported in 1984.

3.2.15 USC-JPL Two Thumbed Dexterous Hand

Shape Adaptation Characteristics - Sukan Lee [3.20] of the University of Southern California in collaboration with the Jet Propulsion Laboratory, has developed a two-thumbed dexterous hand (Figure 3.19) with shape adaptation composed of two articulated thumbs and one articulated center finger. The two-thumbed hand structure provides for stability in adapting to various possible configurations, mainly the right-hand and left-hand configuration in which the two hands are integrated. It also has structural symmetry and balance which is needed in industrial applications.

The shape adaptation feature of the USC-JPL hand reduces the control complexity of the hand and allows for reliable and robotic grasping and manipulating of various objects for a variety of tasks. The USC-JPL hand could be considered anthropomorphic in its function. The hand can be visualized as a human right hand or human left hand or as a hand composed of a right and left hand overlapped. While these are all possible, it is admitted that the hand is not completely anthropomorphic, since it has only three as contrasted to five human digits.

Another notable feature of the USC-JPL hand is a shape adaptation mechanism which allows each finger to automatically configure itself for adapting to various shapes of objects, this feature reduces control significantly by controlling three finger joints of each finger with only one actuator.

USC-JPL Hand Design & Structure - Each of the thumbs which are positioned on either side of the hand have three rotational axes for the three joints at each thumb-base, and two additional rotational axes for flexion and extension. Similarly the center finger has two rotational axes for the two joints at the base, and two additional rotational axis for flexion/extension along the finger [3.20]. Spatial rotation about the z-axis allows the whole thumb to rotate between the upward facing and downward facing positions. This motion cannot be performed by the center finger.

The USC-JPL hand rotations are powered by a DC motor through a tendon connection. The hand has 14 joints controlled by eight motors, three for controlling the yaw angles of three fingers, two for controlling the roll angles of two thumbs, and three for controlling the bending of three fingers through the shape adaptation mechanism.

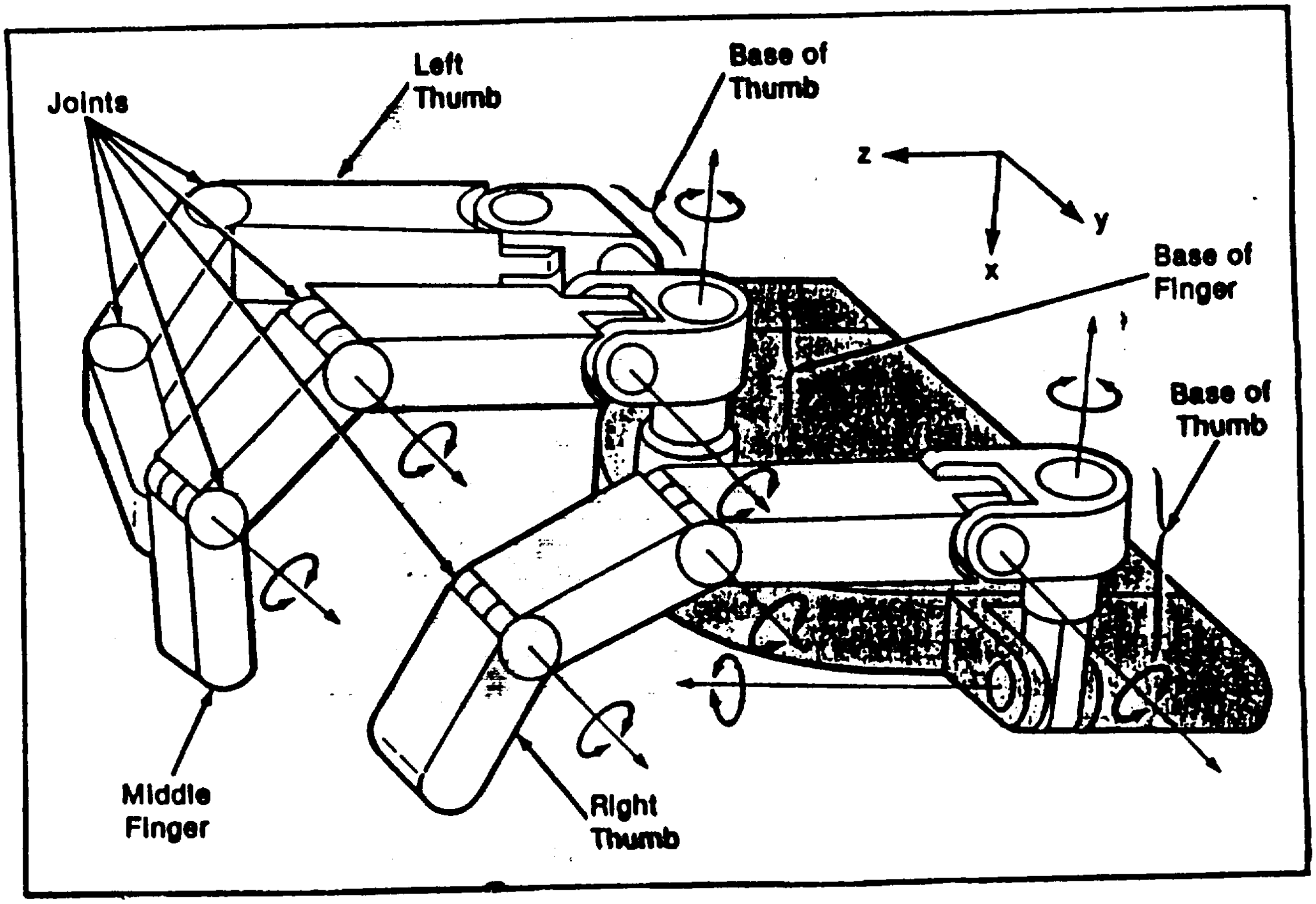

Joints
Left Thumb
Base of Thumb
z
y
x
Base of Finger
Base of Thumb
Middle Finger
Right Thumb

Figure 3.19 USC-JPL Two-Thumbed Dexterous Hand

3.2.16 Toshiba Hand (I)

The Toshiba hand (I) [3.21] developed in the late 70's by Toshiba Corporation for materials handling and TV tube repair is a two fingered, six degree of freedom, non-anthropomorphic hand which is more powerful though less dexterous than the Tokyo hand. It weighs 3 kg and can deliver a payload of 10 kg. It has a frequency response of 3 Hz.

A drive cylinder rod in the wrist of the robot allows for hand clamping action. The direction of the hand shifts 90o from the direction of the cylinder rod as the handling cylinder is set in the robot. The pawl of the hand is coated with rubber and can handle glass material such as brown tubes. The cylinder stroke for the hand is 30 mm and the hand has a grasping force of 392 N. The Toshiba hand is effective in installing a cylinder shifted 90o from the hand.

3.2.17 Wright Robotic Hand

Performance Characteristics - Scott M. Wright [3.22-3.26] of Wright Robotics, Mineral City, Ohio, has developed a remotely operated, dexterous robotic hand (Figure 3.20) that is a prototype for those that would be used in hazardous environments. This full scale robotic hand is anthropomorphic in design and incorporates tactile sensing features. It has three fingers with a total of five degrees of freedom - two for the independent index finger and the coupled second finger, and one for the thumb. The hand, which is made of aluminum, weighs approximately two pounds and has a natural frequency of 2 - 3 Hz.

The payload characteristics vary according to the finger reference. For the thumb, the payload specification between the tip and the joint is 3.95 N. For the index and second finger, at a point located between the two joints, the payload specification is 7.9 N and 3.95 N, respectively. The payload specification at a point on the index and second finger between the tip and the second joint is 2.64 N and 0.88 N, respectively.

Master/Slave Control - The principal of operation of the hand is based on the master/slave controller concept. A hand master referred to as the MIMICTM glove (Multi-degree-of-freedom Integrated Master Interactive Control glove) interfaces with the Wright Robotics hand to effect dexterous manipulation. The fiber optic control glove system senses the operator's finger movements, and uses these signals to control the robotic hand. The Wright Robotics hand design and construction allows for a hypersensitive link between the operator and the dexterous hand.

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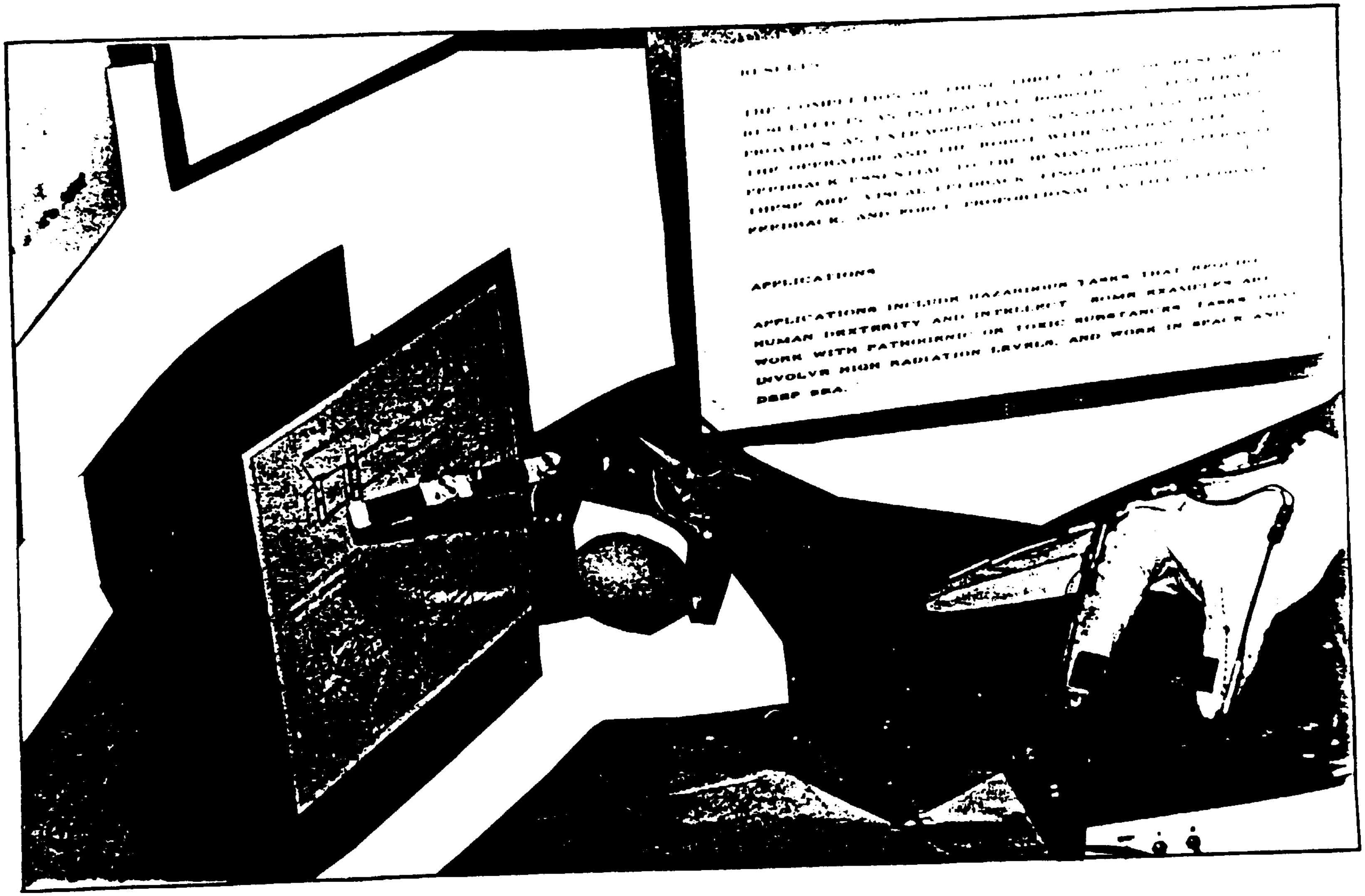

Figure 3.20 Wright Robotic Hand

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Force & Tactile Sensing - The Wright hand has force and tactile sensing feedback. The force proportional tactile sensing system employs load cells to detect the forces applied by the robotic fingers and simulates these forces, with vibratory pulses transmitted as a sense of touch on the operator's respective fingers.

Electronics Interface - The Wright robotic hand system incorporates a real time radio controlled analog system for communication between the MIMICTM glove and the dexterous robotic hand. The MIMICTM glove [3.22] currently has four instrumented joints, and has the capacity for expansion to 20 joints. Position control is currently effected by transformation of resistance changes into electrical signals.

The analog control capability of the Wright Robotics MIMICTM glove is currently being expanded to accommodate software for real-time information acquisition, processing, and control. The C-language software environment is utilized.

3.2.18 Okada Hand

Mechanical Design Features - Okada [3.27] developed a notable compact multi-jointed hand which is anthropomorphic in configuration and characterized by a high level of dexterity. The three digit hand supports an arm having 5 degrees of freedom, a thumb with three degrees of freedom, and two fingers with four degrees of freedom. The hand has the capability of manipulating rectangular and spherical objects in addition to the performance of such tasks as hook, lateral, and tip grasping motions. Using this hand, adduction and abduction motions are possible, in addition to simple bending and extending motions.

The general solution for the finger joint has been provided by Okada who solved a fourth degree equation relating to the joint angles that locate the fingertip. The fourth-order equation is reduced to an auxiliary cubic equation by Ferrari's method and the resulting cubic can be solved; for example, by the use of Cardan's formula. This solution will allow for the position of the fingertip to be precisely controlled.

Each finger in the design of the Okada hand has a circular shape and this shape has been chosen to suppress the visual effect of the rapid change of the grasping condition which arises during complicated finger motions.

The Okada hand has a frame that is made of 17 mm diameter free cutting brass rods which are bored and rendered cylindrical. To achieve compactness and ensure flexibility, the cables, hoses, and sensor signal lines are routed through the finger tubes.

The distortion angle of each joint and the corresponding torque generated are indirectly detected from a potentiometer and a value of the motor current in the trunk respectively. The motors for driving the finger joint are located in a trunk separated from the fingers. Stranded stainless steel cables connecting each finger joint to the corresponding driving motor are about 170 cm long. The finger subsystem which weighs 240 gm can hold objects as heavy as 500 gm.

3.2.19 Belgrade Hand.

The Belgrade hand [3.28, 3.29], developed in Yugoslavia, is an anthropomorphic dexterous hand having five fingers but controlled by only two motors. This allows a selection of two grasp modes : a three finger mode and a five finger mode. There are no tendons for the Belgrade hand; rather, a sophisticated mechanical linkage makes it possible for the fingers to close as far as possible.

Hand Design Considerations - The Belgrade hand which has a direct drive motor that consists of a sophisticated mechanical linkage has touch and slippage sensor abilities. The Belgrade hand has been designed to be mounted on a Puma 560 manipulator for testing and fabrication of the controller. Other tasks the Belgrade hand can perform include :

1) Integrating a three dimensional vision system with the robot controller.

2) Developing, controlling, testing and evaluating.

3) Analysis of human hand structures and control strategies guided by a postulate of the reflex arc.

Information Processing Model for Robotic Control - The reflex arc postulate submits that sensory input to the brain results in complex cognitive and computational processes which include pattern recognition, structured position selection, trajectory planning, etc., and it provides output signals to the muscles which in turn alter joint states to produce a desired motion.

The reflex control principle implies that there are motion patterns which are triggered by specific sensory input patterns, and these are run to completion without further intervention from higher centers in the nervous system. The principle is also based on the assumption that much of the reaching and grasping behavior of humans is derived from a knowledge base which is developed and refined through experience beginning in early childhood and which appears to be quite similar across large human populations [3.28].

Belgrade Hand Computer Architecture - The architecture of the Belgrade hand consists of such components as a microprocessor based hand controller computer (HCC) which receives input from a LISP machine and provides output to the hand drive motors, a VAX 750 computer which is used for the vision (image) system information processing and trajectory generation, and a PUMA control computer which provides input to the joint motors. The LISP machine is used for all processing of the knowledge-base information and inferences regarding the grasp parameters [3.28].

The synthesis of the control required by the Belgrade hand is executed on the computer through the network architecture. The synthesis is based on analysis of the grasping task as performed by human beings, which task can be broken down into [3.28] :

1) **Target approach phase** - during which identification, structure and mode selection, approach trajectory, and hand orientation are effected

2) **Grasp execution phase** - during which shape and force adaptation are imparted to the arbitrarily shaped object being manipulated.

These philosophies capture the essence of reflex control which relies on sensory data and rules of behavior extracted from the human experience and expertise in the tasks to be executed.

3.2.20 Maryland Modular Dexterous Hand

Loncaric et. al. of the University of Maryland Systems Research Center have developed a modular non-anthropomorphic dexterous hand (Figure 3.21) which is a compact, motor driven, three-fingered articulation device [3.59]. The hand was developed based on the "division of function" principle which recognizes the need for a robot to perform a) fine grasping of objects of various shapes and sizes, b) fine manipulation of grasped objects with precision, speed, and well controlled mechanical impedance, c) movement of grasped objects within a large workspace. The Univ. of Maryland hand has been designed to decouple the three functions itemized above. The hand consists of mechanical and electrical components.

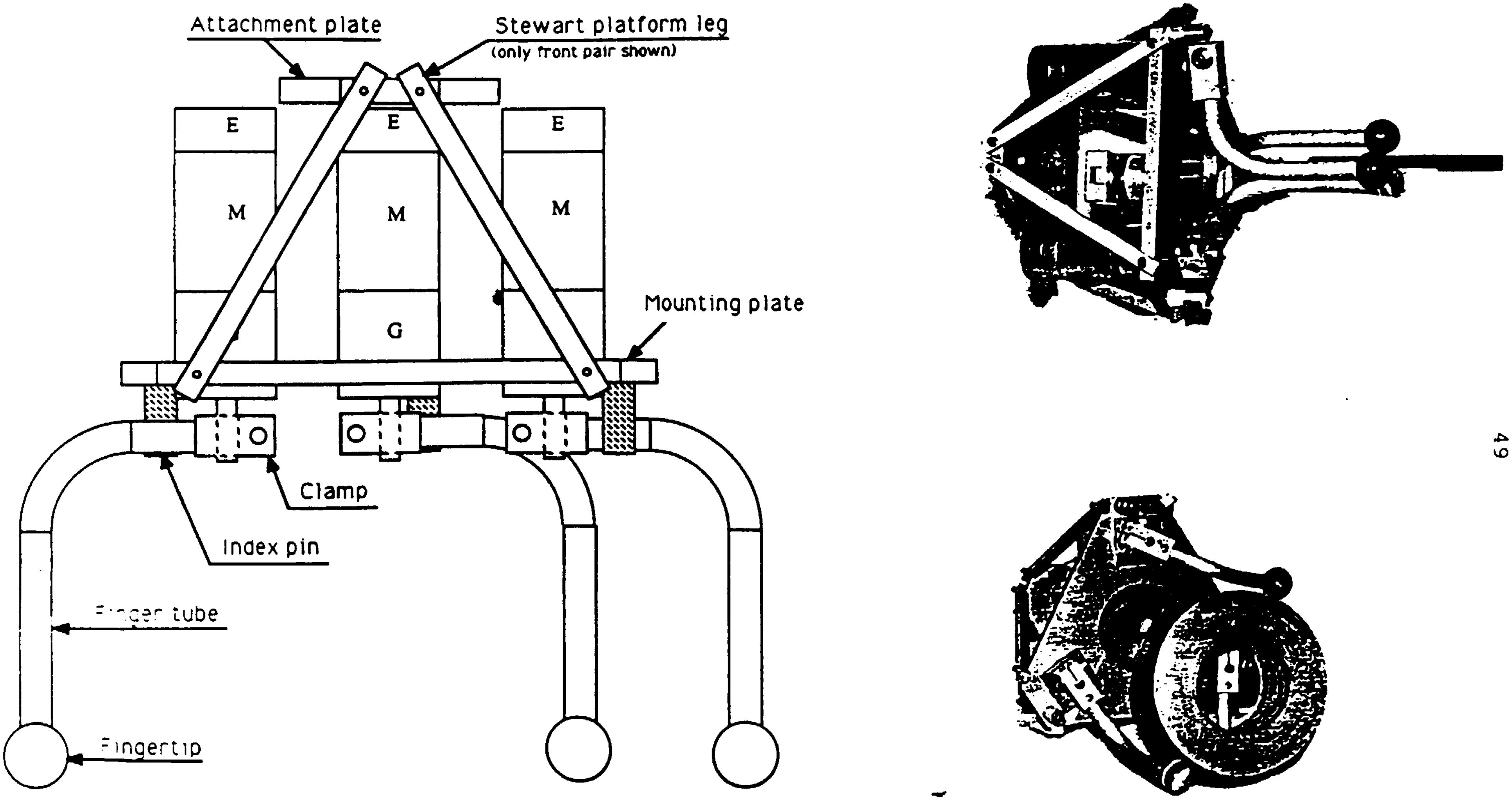
Attachment plate
Stewart platform leg
(only front pair shown)
E
E
E
M
M
M
G
Mounting plate
Clamp
Index pin
Finger tube
Fingertip

Figure 3.21 Maryland Modular Dexterous Hand

The mechanical components include an attachment plate and a mounting plate linked together by a Stewart platform in the front and rear of the supporting structure.

The electrical components include electric motors and gear assembly and/or torque transmission devices that drive the output shafts. The finger assembly consists of three bent tubes, each of which is attached through shafts and clamping devices to motors that make it possible for the three fingers to perform rotary grasping and clasping motion. The finger support assembly is similar in function to "an anthropomorphic palm" that establishes finger orientation and position. The linked structure assists in holding the tubular fingers in place.

Finger motion, aided by the finger tubes and finger tips, facilitate the task of picking and placing objects of varying geometry and size. The hand allows for large motions, fine manipulation and grasping and is well suited for a wide variety of grasps based on three point contacts that leverage the effects of friction [3.59].

3.2.21 Southampton Hand

Crowder and Lacy [3.31] have developed the Southampton hand which could be used in teleoperated mode for material handling in hazardous environments. The hand which is anthropomorphic in design, has also been designed for use with dangerous materials in industrial environments. It has been employed in medical applications for over 15 years and is capable of tactile sensing.

Performance Characteristics - The Southampton (European) hand, which is controlled by use of a series of miniature electric motors, has three fingers and a thumb totaling 15 degrees of freedom. It is a full scale hand with a payload of less than 2 kg. It has a repeatability of +/- 0.1 mm. The hand is capable of moving in a 180o arc in one (1) second.

For power transmission, the finger uses a brushless DC motor with a three-phase MOSFET inverter and a Hall effect sensor. The programming language used for the system development is LISP based.

3.2.22 Utah/MIT Dexterous Hand (Version I & III)

The Utah/MIT dexterous hand (Figure 3.22) has been developed jointly by the Center for Biomedical Design at the University of Utah and the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology [3.32]. Jacobsen et al. [3.32] are credited with developing the very significant high performance multi-fingered robotic hand. The hand has experienced a few evolutionary changes since its initial development [3.32].

The earlier version, the Utah/MIT hand version 1, is a tendon operated, multiple-degree-of-freedom robotic hand with multi-channel tactile sensing capabilities.

Hand Development Goals - One goal of the hand development effort was the provision of an analog tool for a better understanding of issues related to machine based artificial dexterity, including machine vision approaches to dexterous hand supervision, and the influence of robot hand geometry on the execution of various tasks. The available literature reports a design through the third version, which was introduced in 1985.

Another design goal was the development of a hand that exhibits static and dynamic performance levels roughly equivalent to the natural human hand [3.33]. The criteria considered important in the design process included speed, strength, hand frequency response, range of motion, accuracy and controllability. Translating these criteria into design constraints for individual hand sub-components has been a major challenge in the development of the Utah/MIT hand.

The hand's latest version (III) [3.33] has four digits possessing 16 degrees-of-freedom. The joints are actuated by 34 pneumatic actuators. A number of external touch sensors are located at various points on the finger, thumb, and palm, for monitoring contacts with objects, while internal sensors monitor the joint angles, and tendon tensions that are used for force feedback control.

Jacobsen et al. [3.33] notes that, although certain aspects of the dexterous hand transformation process can be analytically described, the precise relationship between the overall hand design and required sub-component performance probably will not be well understood until an operational device can be experimentally evaluated. Therefore, in the design of the first version of the dexterous hand, the major design decisions were based on limited analysis and engineering judgment. Each version of the Utah/MIT hand was developed based on the accumulated experience in designing the earlier versions of the dexterous hand.

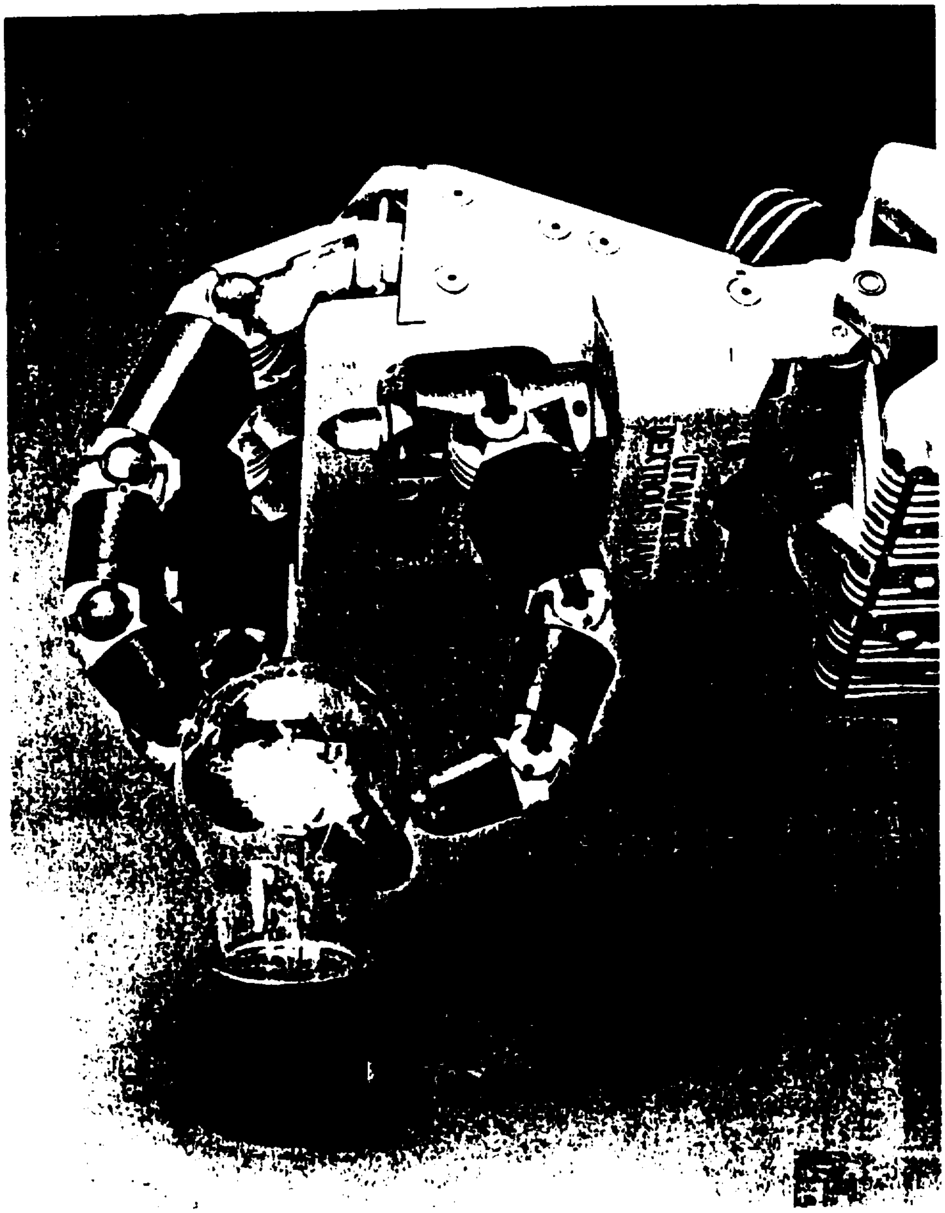

Figure 3.22 Utah MIT Dexterous Hand

Hand Design Considerations - The UTAH/MIT dexterous hand design effort consists of two broad components :

1) Component design features
2) Control system development features

The component design features include the structure, tendons, actuators, touch sensors and other instrumentation including joint angle sensors, and tendon force transducers. The control system development consists of the various systems and sub-control systems that enable joint angle commands to be operational, using servo-systems at each joint, so that the hand assumes various desired configurations.

Structures of the UTAH/MIT Hand - This includes the finger, thumb, palm section and wrist. The internal components of the assembly include joint bearings, tendon terminations and tendon routing pulleys. Each finger in the Utah/MIT hand has three parallel axis joints which provide for curling action, while a fourth proximal joint, which is non-anthropomorphic and perpendicular to the other axes, provides side to side motion of the fingers. The curling joints on each finger provide approximately 90 degrees of excursion, while the proximal joints provide side to side motion and allow a total lateral excursion of + 20o.

The thumb possesses four degrees of freedom, and provides approximately anthropomorphic motions during lateral or palmar grasps. This is very similar to the operation of the human hand. The palm provides structural support for the fingers, the thumb and the wrist. It also provides a transition for the thirty two tendons that originate from the fingers and thumb, and pass through the wrist to the actuation system located on the forearm.

The wrist, which has three degrees of freedom, is spherical and orientates the hand through desired ranges of motion. The wrist is tendon operated. Figure 3.23 shows various hand grasp configurations.

Tendon Design considerations - In version III of the Utah/MIT hand, a wrist tendon configuration allows for synergy of motion and torque between the wrist tendons and the tendon set that actuates the fingers and thumb. The tendon system for the three curling joints consist of six tendons that are synergistically configured as antagonistic pairs [3.33, 3.34]. The proximal joint is configured with two simple antagonistic tendons.

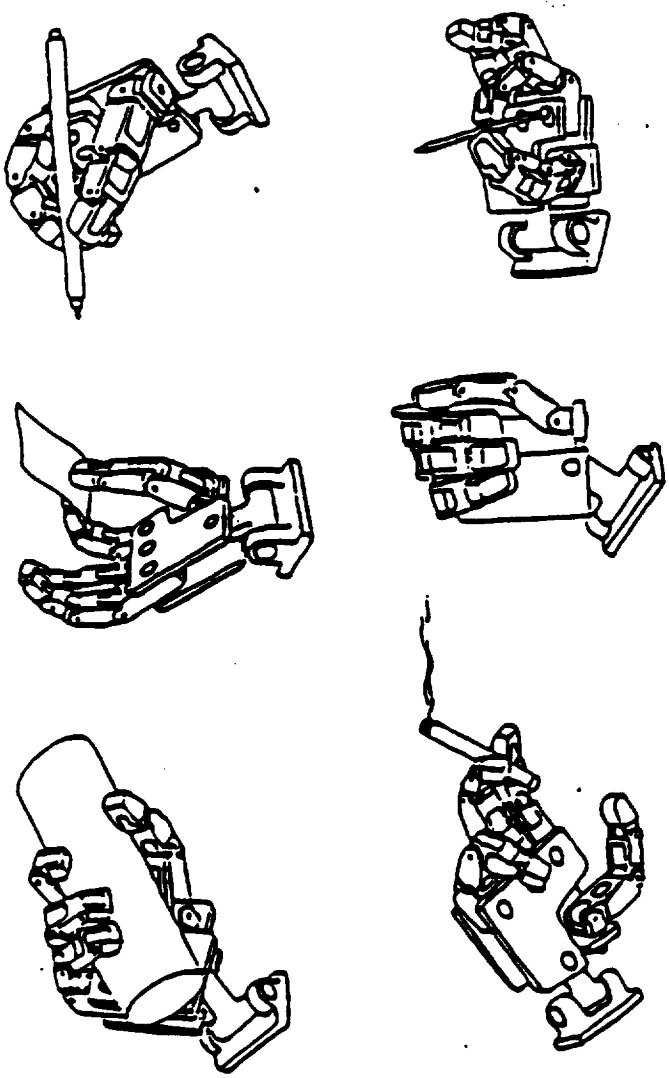

Figure 3.23 Utah/MIT Hand in Various Grasp Configurations

In version I of the Utah/MIT hand, the tendons are internally routed over pulleys. Version III has been improved by development and implementation of a lubrication system that permits tendon routing over fixed surfaces.

Careful consideration was given to the mechanical termination of the tendons. This is important because inadequate designs could seriously degrade tendon strength and lead to the onset of fatigue, which would lower the reliability of the robotic system.

At the distal end of the tendon, termination is achieved through a loop-over arrangement while, at the proximal end, termination is via a clamping system. These designs have been made to be simple, and allow for self-feeding of the tendons to compensate for wear.

Several important considerations went into the choice of tendon materials. Problems associated with strength versus fatigue life eliminated the use of sheathed steel cables, though the use of such cables is extensive in common mechanical systems. This problem of fatigue life is accentuated if the cables are routed over small pulleys that produce high internal bending stresses. Moreover, it was noted that the metallic straps exhibit total, rather than gradual failure, due to their monolithic structure, low lateral compliance, and the unpredictability of their fatigue life, especially under the variable loads that are experienced in dexterous hand operations. These considerations ruled out the use of metallic strap material for the tendon system [3.33, 3.34].

The tendon systems in the Utah/MIT hands were made of high strength polymers. A composite belt constructed of polymeric fibers and sheets was used. Such systems experience low internal bending stresses, have higher lateral compliance, which allow the tendons to be more safely routed over small radii convoluted pathways [3.33, 3.34]. One current tendon design used consists of a multi-fiber Kevlar and Dacron composite. The axial Kevlar fibers support tension loads, and the Dacron mat, which is interwoven with a Kevlar, provides abrasion protection for internal structures. These materials were found to hold a load of 90 N under a 15 million cycle loading. The design goal was 300 N ultimate strength and a 100 million cycle fatigue life for projected uses in the dexterous hand. The tendons used are 3.2 mm wide and 1 mm thick approximately.

Actuators - Realizing that ultimate mechanical performance is dependent on the selection of suitable individual actuators, a pneumatic actuation system was finally selected as the most desirable. This pneumatic approach provides a low weight, compact actuator that can generate required speeds and forces.

A number of electrical systems utilizing DC servo-motors were considered and rejected on the grounds of weight, cost, size and the inability of electrical systems to support static loads in an efficient manner.

Hydraulic systems were rejected for such reasons as difficulty with component availability, weight, stiction, control requirements, leakage requirements and intrinsic dynamic characteristics, which were poor.

The pneumatic system consists of a 1.6 cm internal diameter glass tube which houses a graphite piston that provides stroke. The graphite-glass combination exhibits low friction and allows a close fit that results in relatively low leak rates. The pneumatic cylinders were configured in a close pack four-by-four hexagonal arrays and stacked in three offset layers to provide up to 48 actuators.

Another difficult phase in the development of the actuator system was the design and operation of the pneumatic valves. This delayed the project several months. Because the pneumatic valves possess significant inherent non-linearities, requiring critical precision in control and exhibiting very complex dynamic and fluid mechanical interactions, extensive testing was done after constructing the final prototype. Tests such as the fixed volume test, oscillating volume test and antagonistic actuator test were all conducted to ensure that the actuator met design goals.

Sensors - The Utah/MIT hand has both internal and external sensors. The internal sensors consists of joint angle sensing systems and tendon tension sensors. To obtain accurate joint angle information for control purposes, the sensors were located at the joint within the fingers. Alternative angle sensing approaches considered included potentiometric, capacitive, optical, and magnetic. The method of joint angle sensing finally chosen was the magnetic approach using Hall effect sensors [3.35, 3.36].

The magnetic method of joint angle sensing is reliable. It is amenable to encapsulation, so that intrusion of dirt and other contaminants is not possible, and produces noise levels that are low. It's signals are smooth enough for direct differentiation to provide velocity information. A drawback to this method arises from errors introduced due to strong magnetic fields; however efforts are being made to desensitize the system to external magnetic fields by use of dual Hall effect systems, which configures transistors in the bridge in order to desensitize the system to such external magnetic fields [3.36].

Tendon tension sensors were introduced in the dexterous hand to provide information regarding the torque imposed on individual joints, as well as the feedback of information to controllers for actuator compensation.

The 32 tendon tension sensors are located in the wrist of the robotic hand. Each uses a semiconductor strain gauge bridge to monitor beam deflection which is proportional to the tendon tension.

Robotic Hand Removable Segment - The finger structure consists of five removable segments which occupy void spaces in the finger structure. These segments are made of mold injected rigid or flexible materials, and allow for tactile sensing transducers which sense direct contact, normal pressure, shear stresses, temperature etc. Communication of the internal hand elements with external sensors is made possible via conduits which run along lateral slots in the finger.

Robotic Hand Covering - The Utah/MIT hand can be operated with the segments exposed, or covered with a flexible glove to isolate internal components from undesirable environmental influences and contaminants. Communication between the internal sensors and elements and the external sensors is possible via conduits which run along lateral slots in the finger.

Data Acquisition - Data acquisition in the dexterous hand is made possible through the low level control system (LLCS) which ensures that all subsystems are operating and utilizing complex analog inputs from higher digital control systems. The LLCS includes 16 variable loop gain position servomotors which operate finger joints and a 32 variable loop gain tension servomotor that modulates actuator behavior, leading to the control of tendon tensions effectively. Signal conditioning and amplification is included and provides [3.33, 3.36] :

1) Current sources for driving the pneumatic values.
2) A means of tendon tension sensor operation and joint angle sensor operation, while monitoring both.

The data acquisition input includes: 16 inputs for control of angular position, 32 inputs for control of desired tendon tension, 16 inputs to vary position servo loop gain, and 32 inputs to vary tendon tension servo-loop gain. The hardware of the 16 subsystems of the LLCS includes 13, proportional multi-color light emitting diodes (LED) for the purpose of diagnostically displaying important system parameters. The console includes sixteen potentiometer inputs for the purpose of manually adjusting joint angles. The LLCS provides analog output of all sensor signals generated within the hand [3.33, 3.36].

Computer Architecture Overview - The computer architecture for controlling the

Utah/MIT hand has been implemented quite successfully with a tightly coupled computer system using Motorola 68000 microprocessors on a VME bus. The system is referred as the CONDOR system in version III of the Utah/MIT hand development project. The earlier version of the architecture is referred to as the MUSE architecture for control of the version I hand. The Utah/MIT hand represents a major success in designing and integrating a very complex mechanical system using high performance actuators. The large amount of computer resources needed for finger control (3-5 Motorola 68000 microprocessors) and the relatively high power consumption of the present pneumatic actuation mechanism are some drawbacks. Some of these issues are addressed in the research by Grissom et al. [3.37]. The anthropomorphic design of the Utah/MIT hand is evident. However, excluding the thumb, the first axis of each finger is fixed with respect to the plane of the palm and in the direction of the finger; hence loss of a measure of the abduction/adduction human dexterity results.

In retrospect, the Utah/MIT hand has been designed to be a functional, reliable, and dexterous machine that can provide long term operation. This is possible because the sub-elements have been exhaustively evaluated, and the design has continually been reviewed in order to provide information necessary to enhance the performance and reliability of future systems.

3.2.23 Stanford/JPL Hand

The Stanford/JPL hand [3.38] is a three-fingered, non-anthropomorphic design of a dexterous hand. The fingers have been designed to provide a minimal system for securely holding and arbitrarily moving objects within the grasp of the dexterous hand.

Mechanical Design Features - The fingers, which are 14 cm in length from the axis of the joint to one of the finger tips, are made of 7075-T6 Aluminum, including the joint and pulleys which are made of Aluminum on steel bushings. The Stanford/JPL hand weighs 1.1 kilograms and has motors which can sustain joint torques at each finger joint with values ranging from 85 to 130 N-mm, with an average of 110 N-mm.

The Stanford/JPL hand design was based on the principles enunciated by Salisbury et al. [3.39, 3,40]. They postulated that the minimal system for securely holding and translating objects within finger grasp is a configuration with three fingers, each possessing three degrees of freedom. Such a three-finger arrangement enables objects to be held in tip prehension, consequently increasing robotic dexterity. Tip prehension, is however, achieved at the expense of a more secure grasp that lacks the full six-degree-of-freedom movement of a robotic finger.

According to Okada [3.27], a minimum of three fingers, each possessing three degrees of freedom is required for dexterous tip prehension. This minimal system allows objects to be held in tip prehension so that each finger contributes to securing and moving the object. The fingers in the Stanford/JPL hand are identical, and are orientated using two fingers and an opposing thumb. The joint design allows the fingers to both flex and hyper-extend. The first and second joint (i.e. the proximal and middle joint) have a range of + 90o while the distal joint 3 allows + 135o degrees of motion.

Fingertip Force Sensing System - To be able to successfully execute dexterous hand motions, the Stanford/JPL hand has a well developed force sensing finger tip capable of resolving the location and orientation of a finger contact with its surface. The finger joints were controlled by a tendon system, which utilized a strain gauge at the base of each finger. The strain gauge inputs are fed into an amplifier for control.

The Pitman model 7214 motor, made of Samarium Cobalt DC torque motor, has a stall torque of 117 N-mm at 15 VDC and drives the tendon capstan through a two-stage 28:1 gear reduction. These motors are remotely located and actuate their corresponding joints through steel cables to keep the weight of the Stanford/JPL hand as small as possible.

Tactile & Force Sensors and Data Acquisition - The Stanford/JPL tactile sensor uses fingertip tactile sensors developed at the University of New Mexico; these sensors were rated superior to the passive tip supplied with the hand initially. The goal of the sensor design was the production of a tactile sensor that is able to resolve the magnitude and orientation of a contact force at the fingertip. The sensor consists of a 3x3 force sensor array, mounted on a cylindrical base with a urethane hemisphere covering the active region on the force sensor.

The force sensor array manufactured by Transensory Devices Incorporated (TSD) in Fremont California, consists of two components, namely: the sensor, and its interface electronics. The sensory package is made up of nine individual elements, arranged in a 3x3 array with each force sensor element consisting of a 2x2 mm silicon chip bonded to a glass substrate, adding rigidity to the sensor while acting as a base for the electrical connection.

Each force sensor in the array requires four electrical connections, i.e. power, ground, control and signal. To obtain sensory information on a particular sensor element, the control line of the element is activated and the signal line is read.

Tendon Tension Sensors - The strain of a cantilevered element over which the tendon passes via a pulley is used to determine tendon tension. The advantage to sensing the tendon tension at the base of each finger lies in the reduction of the non-linear effects of friction in the drive train, since the tension in the cable is increasingly reduced along its length by the friction between the cable and its guide.

Interface Electronics - The interface electronics perform several tasks, including supply of regulated drive voltage to the sensor array, multiplexing of the signal and the control line, analog to digital conversions of the sensor output, and communication with the host computer. Communication is carried out over an RS232C serial link through a DEC PDP 11/73 host computer that requests information from the matrix of sensors by sending the address of the single sensing element encoded as an 8 bit word [3.39, 3.40].

The interface electronics respond by enabling the correct sensor, converting the signal and compensating for any sensor offset, while returning an 8 bit word proportional to the force applied to the sensing element. Through this arrangement of small semiconductor strain gauges on metal fixtures, the force and moment exerted on the sensor can be calculated and the resultant forces and moments acting on the finger tip can be used to determine the line of action of the contact force. Using vector analysis of the line of action of the contact force, when mapped onto the geometry of the sensors, could lead to a unique determination of the point of contact of the force impinging on the tactile sensor [3.39, 3.41].

The Stanford/JPL Computer Architecture - The control of the Stanford/JPL hand requires the simultaneous control of twelve (12) DC torque motors to produce the movement of the nine joints belonging to the three fingers. A hierarchically controlled computer architecture scheme was implemented [3.40, 3.41].

The Stanford/JPL computer architecture consists of an LSI-11/73 controller, which commands a microprocessor based Galil DMC 100 servomotor controller for each motor. A Q-bus connects the LSI-11/73 computer to the parallel interface linked to the 12 motors. Each motor requires a servo amplifier, the Pitman 7214 torque motors remotely located from the finger, and a HP 500 line encoder which communicates with a Galil DMC 100 servomotor controller which is linked through a Q-bus to the LSI-11/73 computer. This computer is capable of receiving tendon tension sensor information which is then fed through a low pass filter and analog to digital converter, and finally used for control purposes [3.41].

Plans are underway to improve the computing power for the hand by using a single board processor and motor controller architecture. This could involve using the VME bus, which allows computation and communication to one finger using one processor. The advantage would include the ability to execute forward and inverse kinematics, and conversion between tendon joint and Cartesian space.

3.3 Product Review: User Interface Devices

Introduction - The master/slave control mode for finger coordination and dexterous manipulation requires the operator to wear a specially instrumented dexterous hand master. This device must produce control signals capable of directing the servomotor actuators of the robotic slave hand in synchronization with the respective positions of the human operator's hand joints. Examples of such devices include the "Exos" Dexterous Hand Master, the VPL Research "DataGlove" and the Wright Robotics "MIMICTM" glove, which are all currently commercially available, though they are undergoing continuing development. Applications of these hand masters and other control devices are described in the following paragraphs, together with a proposed new concept utilizing real-time image processing of a special optically patterned master glove.

3.3.1 VPL Research DataGlove

VPL Research of Redwood City, California markets the DataGlove (Figure 3.24), an ingenious glove-like dexterous hand master that senses hand gesture position and orientation in real time [3.47]. The device utilizes fiber-optic cables sandwiched between a stretchable inner glove and a cloth outer glove. Each joint motion to be detected requires a separate fiber-optic cable laid in a parallel path running across the joint and looping back, so that both free ends are anchored in an interface board mounted near the wrist. At one end of the cable is a light emitting diode source, and at the other a phototransistor. The segments of the cable which rest over the joint are specially treated so that the light escapes when the joint is flexed. The greater the degree of bending, the greater is the loss of transmitted light. This effect can be detected by the phototransistor and calibrated to provide angular measurements with a resolution of one degree. A data acquisition rate of 60 times per second is used. VPL Research has also developed a counterpart of the DataGlove hand master called the DataSuit which provides configuration data for the entire body.

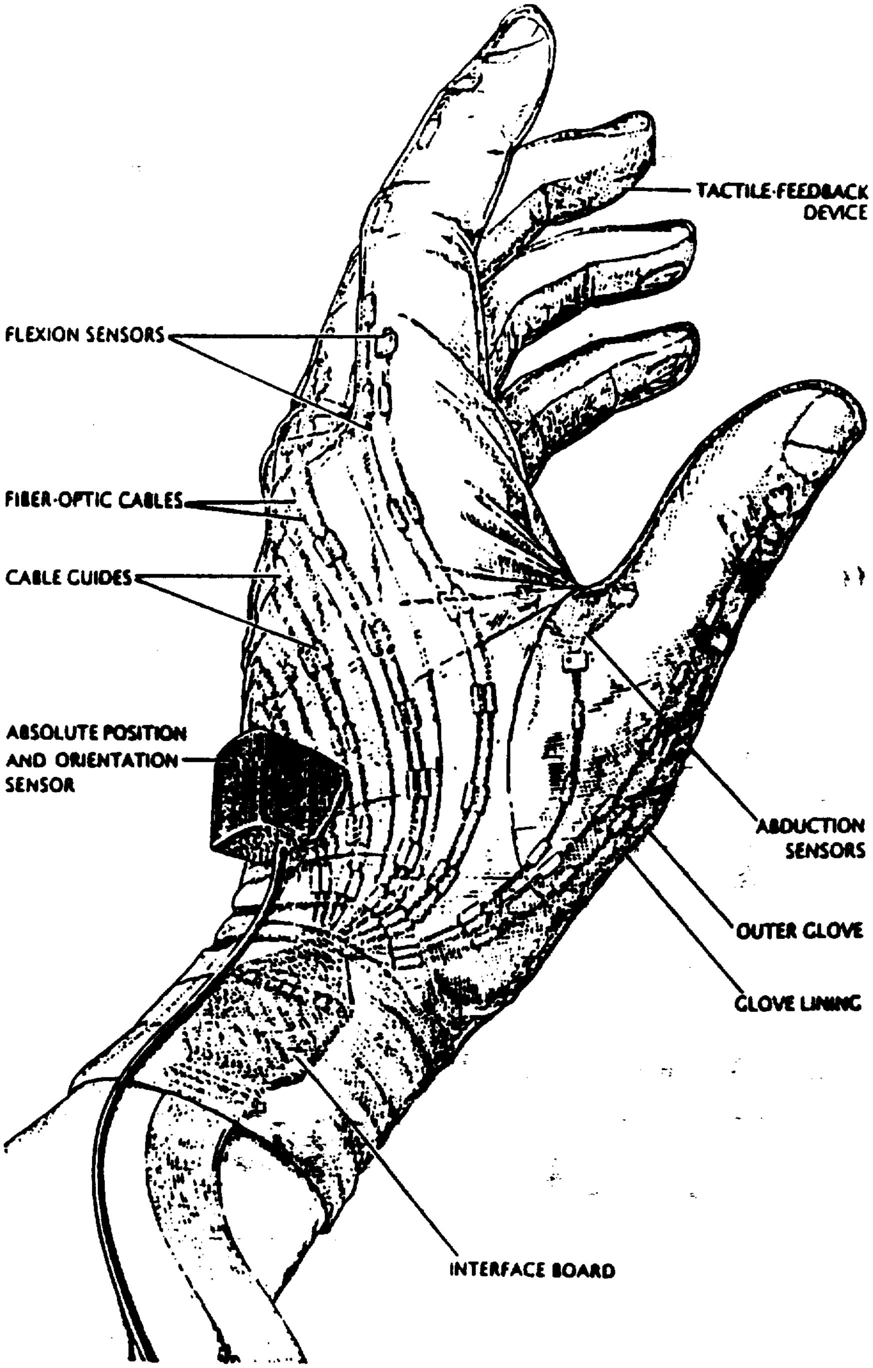
TACTILE-FEEDBACK DEVICE
FLEXION SENSORS
FIBER-OPTIC CABLES
CABLE GUIDES
ABSOLUTE POSITION AND ORIENTATION SENSOR
ABDUCTION SENSORS
OUTER GLOVE
GLOVE LINING
INTERFACE BOARD

Figure 3.24 VPL Data Glove

3.3.2 Exos Dexterous Hand Master

The Exos Dexterous Hand Master (DHM) (Figure 3.25) which is available from Exos Corporation, performs direct readings of any hand joint movements of the hand to which it is attached [3.48]. The sensors are Hall effect devices mounted on the structure near each joint. Each sensor provides a sinusoidal voltage output proportional a joint rotation, and its positioning is such that the range of motion is roughly within the most linear portion of the sine curve.

An electronic board made by Exos provides the power and sensing for the DHM. Exos also provides an optional attachment to measure wrist motion.

3.3.3 Arthur D. Little Sarcos Hand Master

The EXOS Dexterous Hand Master was originally developed by Arthur D. Little, Inc. of Cambridge, Massachusetts [3.51, 3.52] and was named the Sarcos Dexterous Hand Master. The device utilizes mechanical linkage assemblies secured to the individual finger digits by means of flexible ring-like bands. Built-in Hall effect potentiometers translate the various linkage motions into electrical signals which can be correlated to the individual finger joint movements.

Up to twenty human joints motions can be monitored with a resolution of one-half degree over their full range for flexion or ab/adduction. Each channel is sampled 100 times per second to provide for real time finger configuration data. Accuracy of positioning and repeatability are said to be strong points of the A. D. Little hand master.

3.3.4 MIMIC^{TM} Control Glove

The Multi-degree of freedom Integrated Master Interactive Control (MIMIC^{TM}) glove (Figure 3.26) developed by Scott M. Wright of Wright Robotics was selected for application to the SLAVE2 finger [3.22]. This system consists of a glove which fits snugly over the operator's hand and which is instrumented with optical attenuators that detect finger joint movements. Each joint to be tracked has an optical attenuator positioned over it to detect its rotational positioning and motion. The glove and its components are lightweight, compact, and natural fitting so that freedom and ease of movement are relatively unrestricted. The glove can be instrumented to track as many as twenty joints on the hand including abduction and adduction movements.

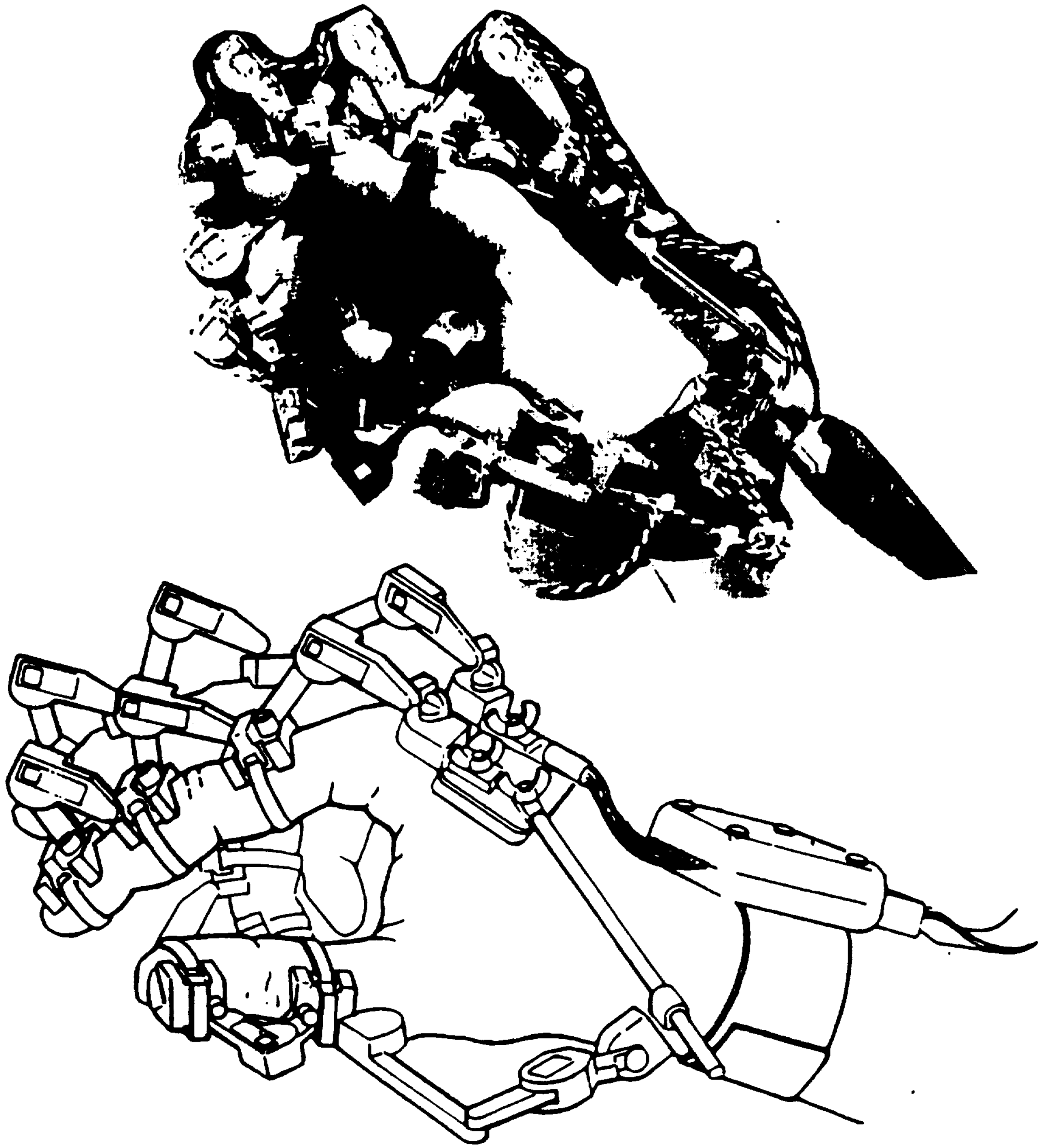

Figure 3.25 EXOS Dexterous Hand Master

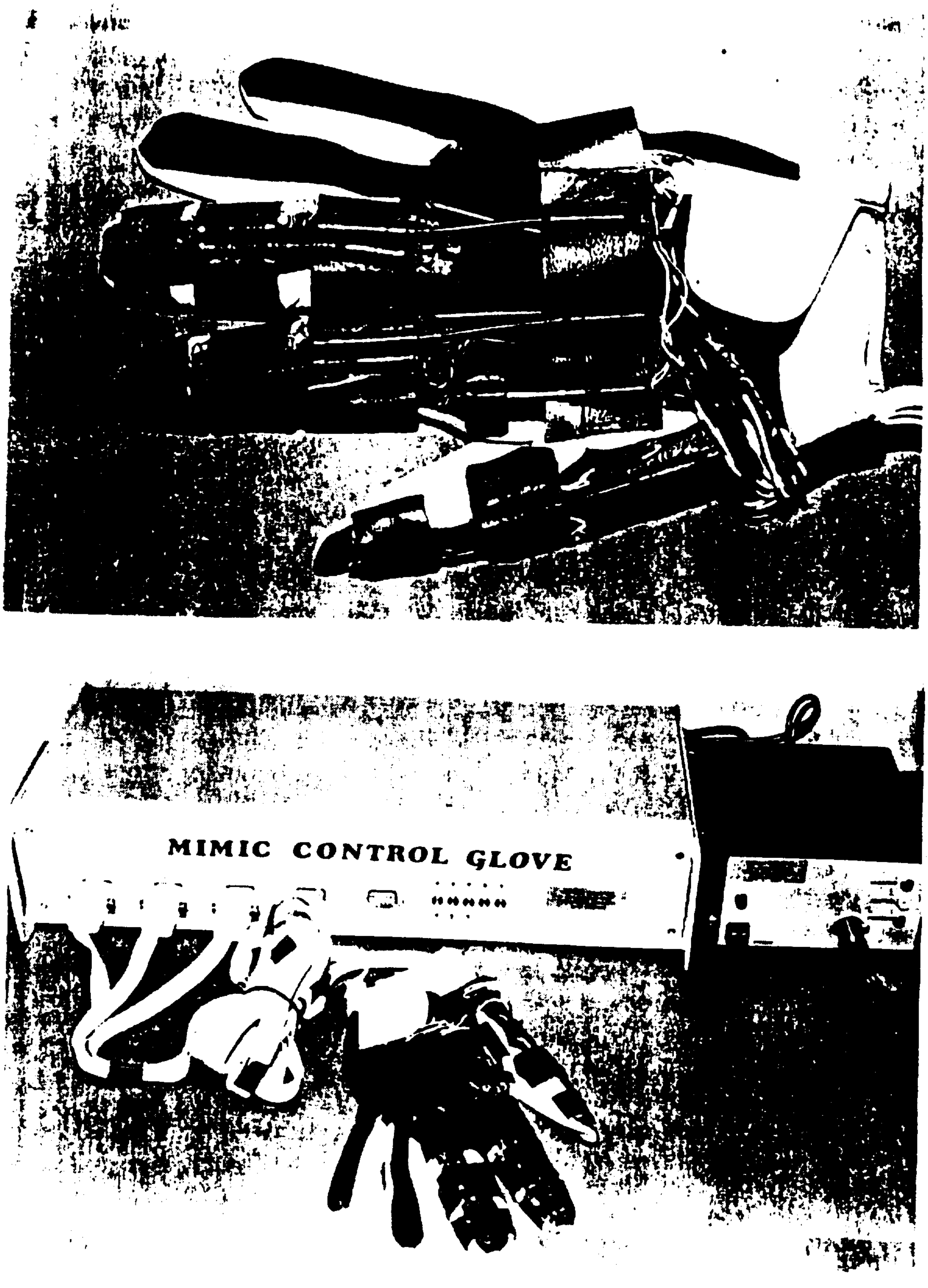
MIMIC CONTROL GLOVE

Figure 3.26 MIMC Control Glove

The optical attenuators which monitor joint positions have a simple configuration consisting of a light source, wave guide, fiber optic probe and detector constructed in such a way that finger motion changes the distance between the probe and the light source to generate a signal proportional to the movement. A conventional operational amplifier circuit isolates the system output and sets signal offsets as well as ramp providing flexibility for integration with diverse systems.

A strong feature of this device is its ability to produce a stable linear response versus movement, thus eliminating the need for complicated and expensive signal conditioning equipment. This capability could also significantly reduce the controller CPU processing time as compared to other master control devices. Strong features of this system are: accuracy of the transducer, (less than one degree), reliability, repeatability and simplicity.

As part of the SLAVE2 phase II effort, a MIMICTM Control Glove, with three fully instrumented fingers (11 axes), custom configured for optimum performance with the SLAVE2 finger, was delivered by Wright Robotics in December 1991. The glove produces control signals from the thumb and the first two fingers of the right hand.

The flexion movement of each digit and the abduction movement of the thumb and index finger are instrumented. The system as delivered is constructed to easily incorporate the articulation of the remaining two digits of the right hand.

3.3.5 Nintendo Power Glove

The Nintendo Power Glove (PG) (Figure 3.27) is a device used to measure hand and finger motion for games using the Nintendo system. VPL Research in Redwood City, California provides the glove with serial adapters, called power glove serial adapters (PGSA), for research use. Using the PGSA, any computer with a serial port can read the information from the glove. The glove information consists of flex data from the thumb and three fingers. New data packet information is uploaded by the power glove serial adaptor at the rate of 30 Hz representing the time required for the PG to calculate and assemble a new data packet.

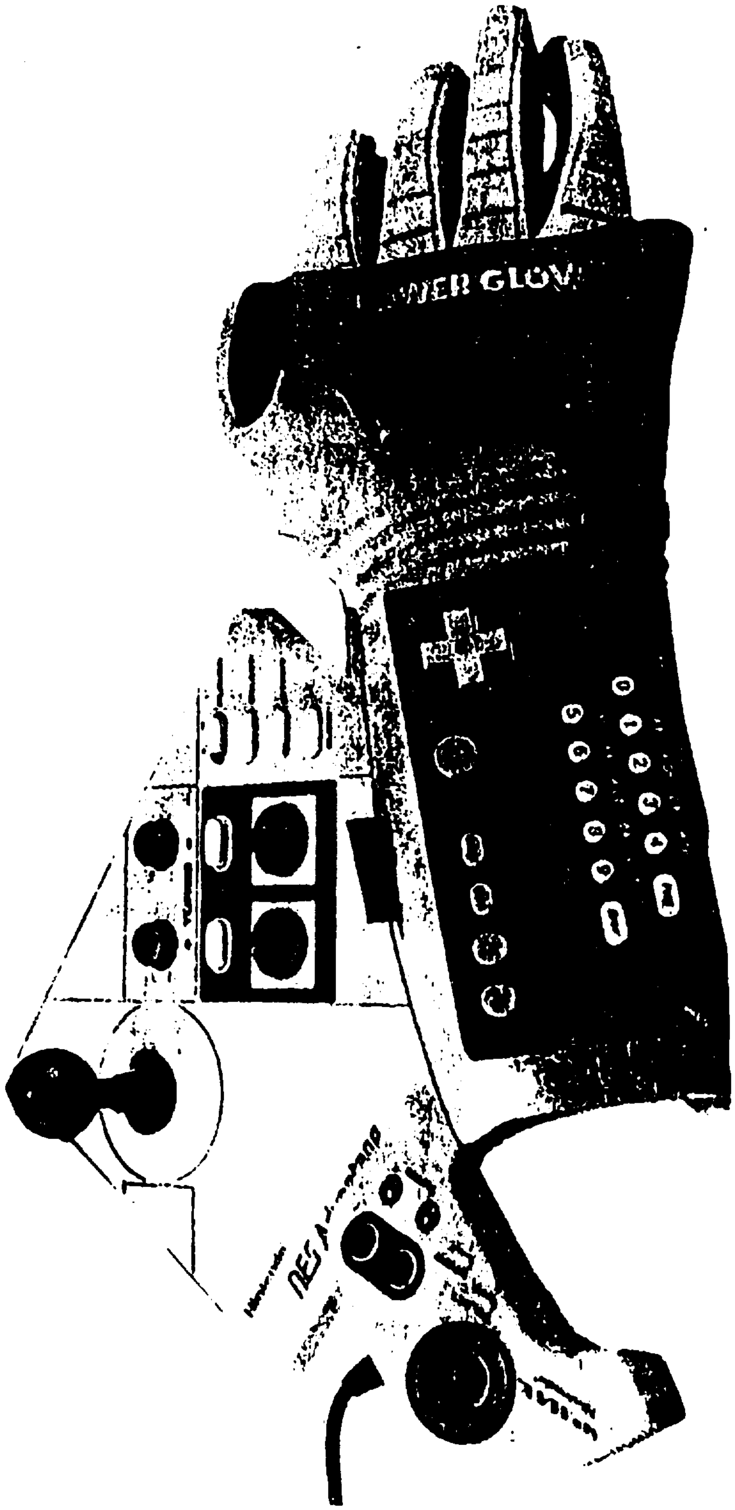
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Figure 3.27 Nintendo Power Glove

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3.3.6 Optical Pattern Hand Master

A third method suggested for the master control mode is the use of a master glove imprinted with a special color-coded optical pattern [3.49]. In this approach, the respective control signals for positioning the multiple finger joints would be extracted from the glove image.

Potentially, the patterned glove could be lighter, better fitting, less cumbersome, and possibly less expensive than either the EXOS Dexterous Hand Master, VPL DataGlove or MIMIC^{TM} Control Glove at the present time. However, no commercially available devices or research prototypes of this nature have been identified to date.

3.3.7 Rutgers Portable Dexterous Force Feedback Master

The Rutgers hand [3.30] developed by Burdea and Roskos incorporates one robot thumb and three robot fingers. The respective joints of the thumb and fingers are controlled by separate tendons that are used to provide opposing forces about each joint to rotate the associated finger element about the joint. The position sensor includes a linear variable differential transformer having an output signal that is proportional to the distance between the user's fingers.

A force feedback system (Figure 3.28), including the pneumatic micro-actuator, senses forces exerted by end-effectors on the robot hand and causes a corresponding force to be reflected to the user. The thumb and finger are controlled by several tendons that are manipulated by a hand controller in response to computer generated signals, also tendon control using strain gauge technology is incorporated. The Rutgers hand is controlled by a master which consists of a compact hand held unit that fits within the space defined by a user's palm and finger. The master functions as position controller for a dexterous robotic hand. The dexterous hand master may be implemented with a conventional dexterous hand such as the Utah-MIT hand.

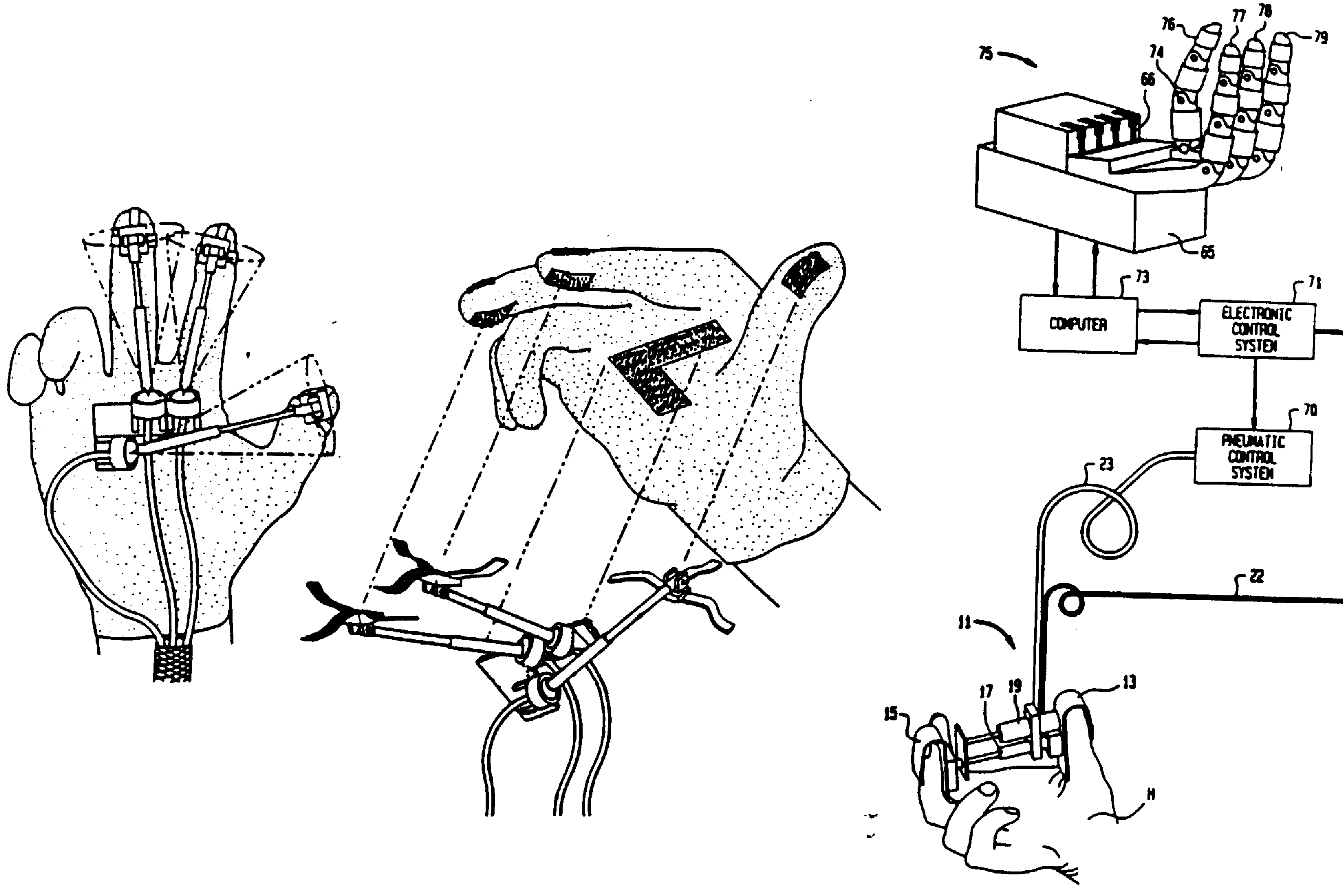
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Figure 3.28 Rutgers Portable Dexterous Force Feedback Master

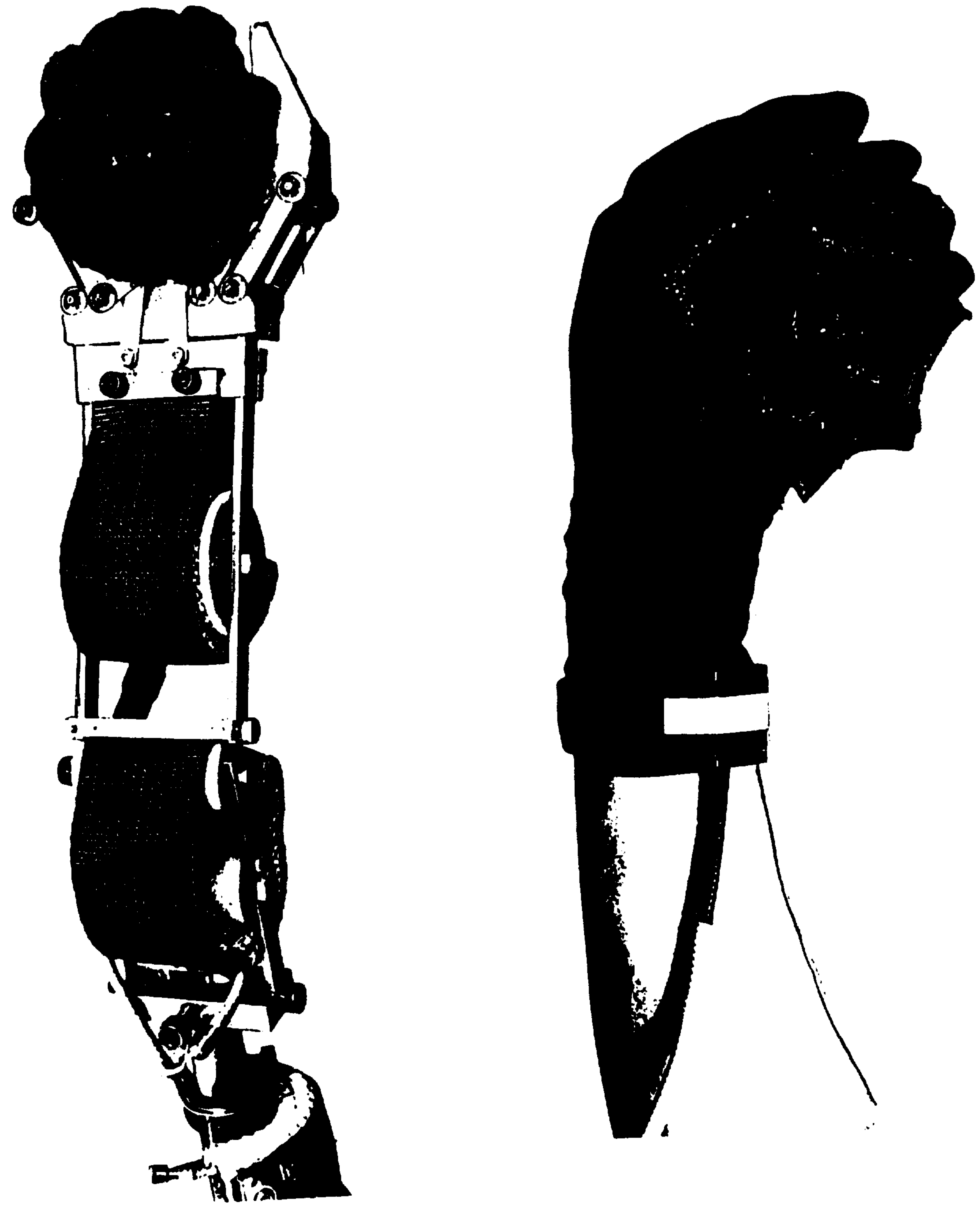

Figure 3.29 Airmuscle Ltd. Teletact

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3.3.8 Airmuscle Ltd. Teletact

Hennequin J. et al. [3.50] of Airmuscle Ltd, Bedford, England have developed the Teletact (Figure 3.29), a glove that gives wearers the sensations and feel of objects transmitted as signals from any distance. The Teletact output glove stimulates the inner surface of the wearer's fingers, thumbs, and palm. The glove has 20 air-pressure pads fed from vein like tubes. Computer regulated solenoid valves control the compressed air that creates the pressure sensations on the skin. The Teletact air glove is often used in combination with a special input glove that has 20 built-in force-sensitive resistors. A user would typically grasp an object while wearing this glove and the force-sensitive resistors vary the voltages that determine tactile pressures in the air glove.

The Teletact concept can also be used in conjunction with the Dataglove developed by VPL Research in Redwood City, California [3.47]. The VPL Dataglove, which has strands of optical fiberglass behind the finger and the thumb, is able to vary light absorption through the fibers proportional to the degree of flexure, and shape change of the finger and the thumb. The variation in the light intensity can be converted into digital signals for analysis in a computer. The digital signals may be used as inputs for the control of an end-effector in a teleoperated environment.

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CHAPTER 4

DEXTEROUS GRASPING AND MANIPULATION FUNDAMENTALS

4.1 Introduction

A multi-fingered dexterous hand can perform a variety of tasks in unstructured environments and accommodate unexpected events. It is capable of different grasp postures and of local manipulation for a change of grasp postures. For instance, a pencil is picked up with a picking posture and then manipulated to a writing posture.

Numerous dexterous hands have been built. One type has an anthropomorphic configuration with 4 or 5 fingers, like the MIT/UTAH hand [4.1], Goddard Hand [4.2], and Belgrade/USC Hand [4.3]. This type of dexterous hand is good for master-slave control with a master control device like the DataGlove [4.4]. The other type of dexterous hand has only three fingers like the Stanford/JPL Hand [4.5], Odetics Hand [4.6], Upenn Hand [4.7]. This type is simple in configuration and can be used in tele-robotic control.

Cutkosky and Wright [4.8] analyzed 16 different types of a human hand grasping and classified them into two basic grasp types: power grasp and precision grasp. Which grasping posture to use depends on the constraints on the hand, the object, and the task.

The constraints on the robotic hand's capability include the largest diameter of a cylindrical object the hand can wrap-around, the maximum span of the opposite fingers, the maximum force each finger can exert, etc. The constraints on the object include the size, shape and weight. The constraints on the task include the external load and the nature of the grasp: for power, precision, or manipulation.

Based on these constraints, one can select a grasping posture. When the posture is a finger-tip grip, fingers should be curved such that the last phalanx is normal to the object. The normal grasping force will then go through the last joint, and no torque is exerted on this joint. This is the way fingers strike the keyboard when typing or playing piano.

A force closure grasp is the case when the contact forces and moments at grasping points can resist the external force/moment in any direction. Form closure can be viewed as force closure with frictionless contact only [4.9]. Reuleaux [4.10] showed that at least four contact points are required for a 2D form closure grasp, and Lakshminarayana [4.11] proved that seven contact points are needed for a 3D grasp. A comprehensive correlation between grasping postures and external loads is derived in the next section.

Grasping control can be characterized in three stages: before, during, and after contact between the hand and object. Motion control is used to control fingers before they contact the object. Force control is used after the contact because the fingers are immobilized and sufficient grasping forces are required to balance the external load. The transition between motion and force control is the compliance control in which the finger is moved proportional to the difference between the desired and actual resisting forces. This can be used to account for positioning inaccuracy.

The motion control must control the motion of fingers simultaneously. The control of a multi-fingered hand can be viewed as that of cooperating multi-arms. Because motion control of one arm (or one finger) is well known, motion control of a dexterous hand is straightforward. That is, if the grasping point and orientation of the last phalanx of each finger are specified, based on grasping analysis, each finger's joint angles can be calculated using inverse kinematics similar to that of a single robotic arm.

The force control is more complex because grasping forces/moments are redundant and their magnitudes are hard to determine. Yashikawa and Nagai [4.12] classified contact force as grasping force and manipulating force. For grasping stablility, force closure [4.13] is that the grasping forces can resist the external load in any direction. Form closure is a subset of force closure where the contact surface is frictionless.

4.2 Grasping Postures and External Loads

The methodology relating grasping postures and external loads derived in this section will determine the number of grasping points required and their positions to balance the external load. The methodology is induced from the finger-tip grasping, but applies to the wrap-around grasping mode as well.

In a finger-tip grasping, the contact area between a finger-tip and an object is limited, and a point contact can be assumed. The frictional moment can therefore be neglected, and only normal and frictional forces should be considered for constraining the external load. The magnitude of a frictional force is proportional to the frictional coefficient. If a task is new and the surface condition is uncertain, frictional forces may be unpredictable and unreliable.

To eliminate this uncertainty, normal contact forces can be considered as primary forces to balance the load, and frictional forces are secondary to constrain the unexpected change of the load. If we consider normal contact forces only, the grasp can be viewed as on a frictionless surface.

Different numbers of contact points are analyzed in the following sections to relate the minimum number of contact forces to the external load. Once the locations of the contact forces are decided, the magnitudes of these forces can be solved through the redundancy analysis.

4.2.1 Two Contact Points

If two normal forces are collinear, as shown in Figure 4.1(a), they can balance an external force along this line, as shown in Figure 4.1(b). The frictional forces can balance the external forces in the other planar direction and the external moment in this plane, as shown in Figures 4.1(c) and 4.1(d) respectively.

4.2.2 Three Contact Points

The three contact forces can be either concurrent or parallel, as shown in Figure 4.2. Three concurrent forces are applied to a sphere or a disk to balance external forces in any planar direction. These three forces have to be arranged in a position satisfying the maximum angle rule, i.e, the angle between two adjacent contact forces should be less than 180 deg. Otherwise if an external force is facing a segment with an interior angle equal to or greater than 180 deg as shown in Figures 4.3(a) and 4.3(b) respectively, the three contact forces can not balance this external force. More contact forces are required in this case.

To grasp a slender object, the three contact forces will be parallel, and one contact force will be opposing the other two. The contact forces will balance the external load in the direction of the normal forces and the moment in the plane. No two of these three forces should be collinear, and the best arrangement is for one finger to aim at the center of gravity (cog), the other two will be symmetric about the cog.

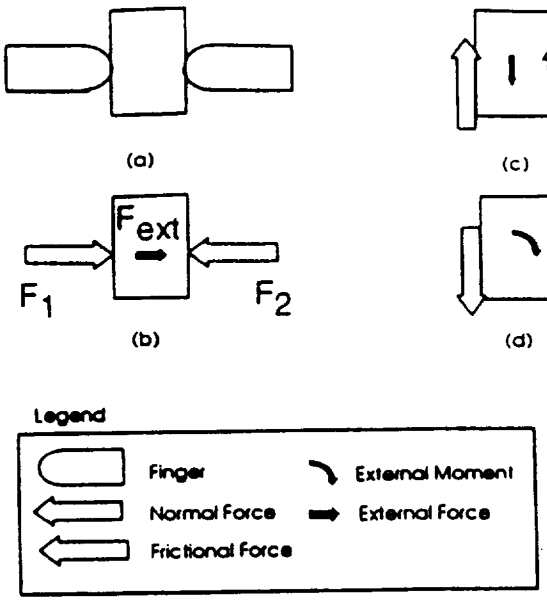

(a)
(c)
Fext
F1
F2
(b)
(d)
Legend
Finger
External Moment
Normal Force
External Force
Frictional Force

Figure 4.1 Two Contact Points

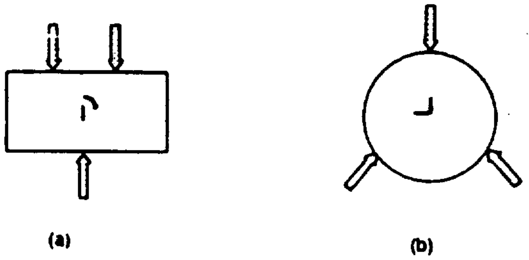
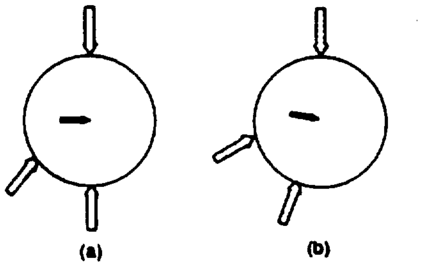


Figure 4.2 Three Contact Points


(a) Two colinear forces

(b) One subtended angel is greater than 180°

Figure 4.3 Incorrect Arrangements of Three Contact Points

The minimum angle rule can be applied to wrap-around grasping as well. Grasp configuration shown in Figure 4.4(a) is not stable because the hand can not hold on if an external force is in the direction of the negative x axis. On the other hand, the grasps in Figures 4.4(b) and 4.4(c) are satisfactory.

These figures can be used to decide the maximum diameter of a cylinder which can be grasped by a multi-fingered hand with 2 or 3 phalanges on each finger. The maximum diameter d is equal to 2a for a finger with 3 phalanges, and d is equal to b for a finger with 2 phalanges, where a and b are respective lengths of the phalanges.

4.2.3 Four Contact Points-Planer External Force/Moment

The four coplanar forces are grouped into two pairs of forces (two couples), as shown in Figure 4.5, to balance any external force and moment in the plane. When the distance between a pair of forces is larger, the magnitudes of the forces are smaller. Therefore, the corner grasp, as illustrated in Figure 4.6, will ensure a stable grasp. If the two diagonals of the quadrilateral object have different lengths, the longer one should be chosen, as shown in Figure 4.7(a).

Because many hands have only three fingers, four-point contact of finger tips may not be possible. The grasp shown in Figure 4.7(a) is a wrap-around grasp with two fingers and the palm. In this wrap-around grasping, line contacts occur between one or more phalanges and the object. The distributed load on a phalanx can be represented by an equivalent contact force, as shown in Figure 4.7(b).

Notice that in Figure 4.7(b), five forces are shown, and one of them can be zero. If F3 is zero, it is a corner grasp. If F5 is zero, the arrangement will be better because F1, F3, and F4 can account for the moment balance, and F2 can be used to balance the external force. These forces are not paired as those shown in Figure 4.6. Nevertheless no two of them can be collinear, and no three of them can be concurrent or parallel.

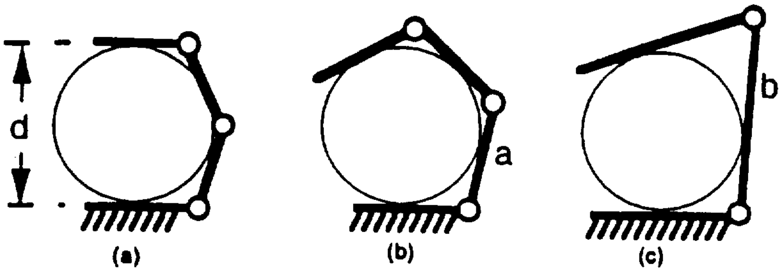


Figure 4.4 Wrap-Around Grasp

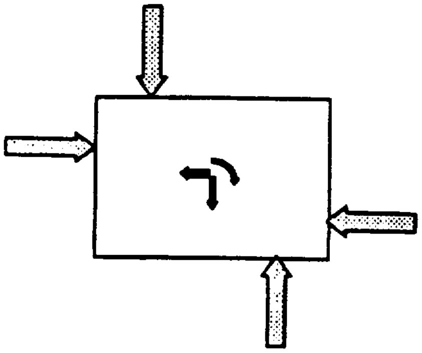


Figure 4.5 Four Contact Points

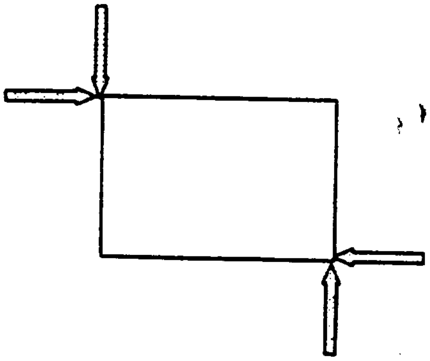


Figure 4.6 Location of Four contact Points

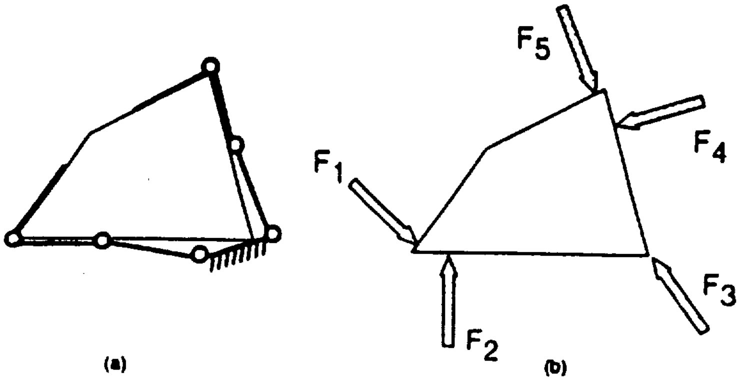

F5
F4
F1
F3
F2
(a)
(b)

Figure 4.7 Four Contact Points

C-2

4.2.4 Four Contact Points- 3D External Forces

If contact forces are required to resist the external force only, for instance when the gravity force of the grasped object is the only concern, four concurrent contact forces are needed to constrain the object. Figure 4.8 shows one example of this arrangement. No two of these four forces can be collinear; no three can be co-planar; and no force can fall in the pyramid defined by the other three forces, as shown in Figure 4.9. Alternatively, we can specify that the extension of any force must fall in the pyramid defined by the other forces.

In the case of three planar concurrent forces, the pyramid is degenerated to a triangle, and the rule is reduced to that no force can fall in the triangle defined by the other two forces. This rule agrees with the one presented earlier that the angle between any two adjacent forces should be less than 180 deg.

4.2.5 Seven Contact Points

From previous cases, we can induce that at least n+1 normal contact forces are required to balance an external load with n degrees of freedom. This is because the normal forces is uni-sense, i.e., compression only. In the most general case, the external load has six degrees of freedom (dof): three dof in the force vector and three dof in the moment vector. The minimum number of contact forces to balance this external load is then seven.

Among these seven forces, no two can be collinear; no coplanar three can be concurrent or parallel; no four can be coplanar or concurrent; and no six forces can intersect a common straight line. For instance, if F5 in Figure 4.10(a) is at the lower right corner, six forces intersect the diagonal. These forces along with F4 can not constrain the moment vector along this diagonal. As explained in screw theory [4.14], when 6 forces intersect a common line, they are not independent, and they belong to a 5 system.

The seven forces can be grouped into four moment vectors, as shown in Figure 4.10(b). These four concurrent moment vectors should be arranged like those four concurrent forces. That is, no two moment vectors are collinear; no three are coplanar; and no any moment vector can fall in the pyramid defined by the other three moment vectors.

The grasping force and moment vectors are related as follows: when two moment vectors are collinear, four contact forces are coplanar; when three moment vectors are coplanar, six contact forces intersect a common straight line. As discussed earlier, if F5 in Figure 4.10(a) is at the lower right corner, six forces intersect the diagonal, and three moments M1, M2, and M4 are coplanar.

Because it is unlikely to have 7 fingers for the finger-tip grasp, line or surface contact will be required to constrain an object completely. One possible grasp is shown in Figure 4.11 where the palm and three fingers are being used. Notice that the distributed load along a phalanx is used to represent two forces, F4 and F5, in Figure 4.10, and these are located at the ends of the phalanx.

The grasping posture discussed here can resist external load with the magnitude within the hand's capability. This also implies that the posture will be stable in the absence of load.

4.3 Redundancy Analysis of Grasping Forces

As discussed in the last section, we need at least n+1 contact forces to constrain an external load with n degrees of freedom. Since the number of unknown is one more than that of equilibrium equations of force and moment, there are an infinite number of solutions. The minimum solution of these forces will be the one with a zero normal contact force. If that force is nonzero, the external force is accentuated.

For instance, in the case of two contact points, only one of the contact forces is needed if the direction of the applied force is known, and the other can be zero. That is, in the equation of F2 = Fext + F1, F1 should be zero. Otherwise, F2 will be increased accordingly.

For three concurrent planar contact forces, the plane is divided into three regions by the extension of these forces as shown in Figure 4.12. When the direction of external force is known, the normal force that falls in the same region as the external force should be zero. For instance, in this figure, the external force is in the region 3, and therefore F3 should be zero. This is because when F3 is eliminated, the remaining three forces (including the external force) will not violate the rule that any angle between two adjacent forces should be less than 180 deg. If the external force is on the boundary of two regions, it is opposite to one contact force. Therefore, the two forces in these two neighboring contact regions can both be zero.

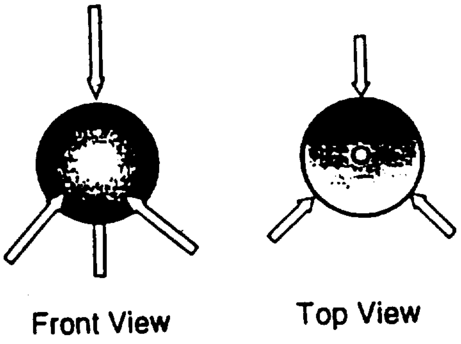

Front View
Top View

Figure 4.8 Four Contact Points 3D Forces

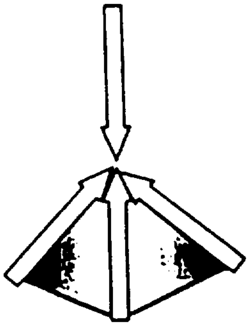


Figure 4.9 Pyramid Forces

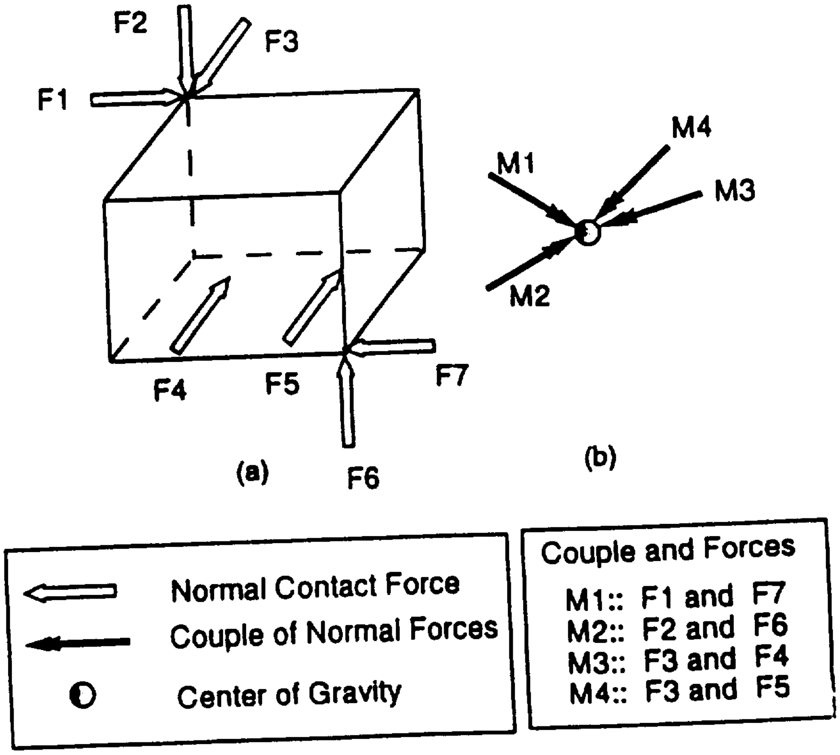

F1
F2
F3
F4
F5
F6
F7
(a)
M1
M2
M3
M4
(b)
Normal Contact Force
Couple of Normal Forces
Center of Gravity
Couple and Forces
M1:: F1 and F7
M2:: F2 and F6
M3:: F3 and F4
M4:: F3 and F5

Figure 4.10 Seven Contact Points

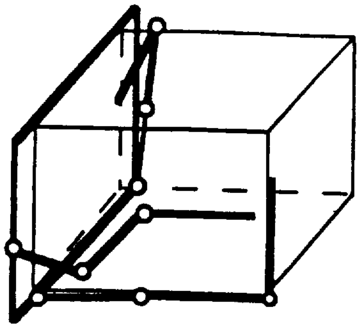


Figure 4.11 Location of Four Contact Points

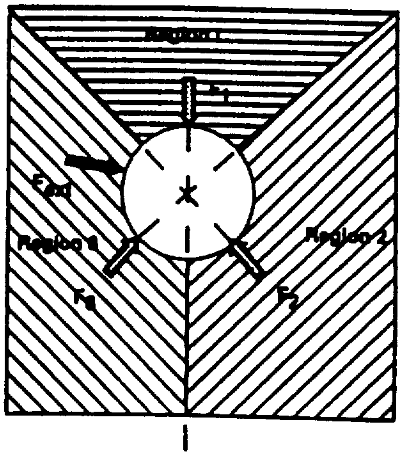

Region 1
F1
Fad
Region 3
Region 2
F3
F2

Figure 4.12 Three Regions Defined by the Three Contact Forces

For four coplanar forces, one pair of forces is to balance the external moment and the external force in that direction. One force of the other couple is used to balance the external force, and the remaining contact force can be free.

For four concurrent contact forces, the extensions of the normal forces can divided the space into four regions. The normal force that is in the same region as the external force should be zero. If the external force is on the boundary of two regions, the normal forces in both of these regions can be zero. This means the external force and the other two normal forces are coplanar, and the later two can balance the load. If the external force is on the boundary of three regions, all normal forces in these three regions can be zero. This is the case when the external force is opposite to the remaining normal force and can be balanced by it.

For seven contact points, there are four moment vectors. Three parallel forces, F3, F4 and F5 in Figure 4.10, account for two moment vectors, M3 and M4. One of F4 and F5 can be zero depending on whose moment vector falls in the same region with the external moment vector, where regions are defined by extensions of moment vectors.

Once one of contact forces is zero, the remaining force system becomes nonredundant, and their magnitudes can be solved by simultaneous equations. If the external force is changing its direction with time, the zero contact force will changes from one contact point to another.

4.4 Conclusions

From induction, we can conclude that n+1 normal contact forces are required to balance the external force/moment of n degrees of freedom. This is because the normal forces are uni-sense, i.e., compression only. If some of the contact forces are arranged in a special way, they are not linearly independent, and more contact forces are required.

Since we need at least one more contact force than the external load's degrees of freedom, the contact force system is always redundant. The minimum solution contains one zero contact forces. Which force is zero depends on the location of the external load.

The grasping postures discussed in Section 4.2 can be used for grasp planning and motion control. For instance, if the gravity force is the only external load on the grasped object and the object will change its orientation about more than one axis along its trajectory, four concurrent normal forces are required.

This information can not, however, decide the exact finger-tip positions, needed for motion control. Further development is required to find these positions based on the object's shape and size and the hand's geometry. These positions must satisfy the rule that the grasping normal forces are independent.

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CHAPTER 5
APPLICATION ASSESSMENT FOR COMMERCIAL MARKETS

5.1 Assessment Overview

To determine present and anticipated future needs for robotic hand devices, a review was conducted of government R&D initiatives as well as industry and university activities. The government R&D information was derived primarily from direct telephone contact with researchers, from technical publications and various government reports. Section 5.2 reports on various government agency initiatives.

A formal mail survey was widely distributed to the broader research community including government agencies. Over 400 copies of the survey were mailed out with approximately a 10% response level. A complete listing of the survey recipients is given in Appendix C.2. Section 5.3 gives the responses attracted chiefly from universities, manufacturers and distributors. Though no currently implemented, robust, dexterous hand applications were uncovered by the study, indications are that the requisite technology is rapidly developing and that near-term future implementations appear feasible. A number of government agencies, industrial laboratories and universities are, therefore, involved in R&D efforts to achieve practical applications of dexterous robotic hands.

5.2 Government Agency Related R&D Initiatives

NASA has identified broad research needs for telerobotics and automation including some applications which might realize significant benefits from dexterous robotic end-effectors. A brief overview of these interests is given in the Section 5.2.1. Likewise, other government agencies are supporting related research and development initiatives to meet their special needs. This includes initiatives emphasizing dexterous robotic hand type devices or related robotic technology. An effort was made to query a wide range of these agencies to uncover existing or developing technology which might be utilized to enhance the ground-based operations at NASA Kennedy Space Center. Following is a list of government agencies or laboratories contacted:

U.S. Dept. of Energy
U.S. Bureau of Mines
U.S. Army Corps of Engineers
National Institute of Standard and Technology
U.S. Air Force Wright Laboratory
National Science Foundation
Federal Aviation Administration
Army Research Office
Office of Naval Research
Woods Hole Oceanographic Institute
Defense Advanced Research Projects Agency

A brief discussion of the various activities is given for a number of these organizations in the following paragraphs.

5.2.1 National Aeronautics and Space Administration (NASA)

Across a broad range of operations NASA has identified needed areas of research encompassing telerobotic or autonomous operations. This applies both for in space and for ground-based operations including transport, inspection, servicing and processing activities. The need for emphasis on such automated operations which would, in many cases, require dexterous robotics is highlighted by the following excerpt from the "1990 Report of the Advisory Committee on the Future of the U.S. Space Program" [5.1].

> "It can be argued that much of what humans can perform in space could be conducted at less cost and risk with robotic spacecraft --- and in many instances we believe that it should be."

Likewise, NASA's recent "Space Technology Long Range Plan - Draft," April, 1991 [5.2], articulates numerous "key or specific" objectives addressing future needs directly related to automation and robotics technologies which might utilize dexterous end-effectors. The following are samples of these objectives which permeate all five basic thrust areas defined by NASA (Science, Transportation, Space Station, Exploration, Breakthrough):

SCIENCE:

"Automated Robotic Assembly of Space Structures by 1996."

TRANSPORTATION:

"Enhance Ground Operations Processing and Checkout of Vehicle and Payload through Application of Artificial Intelligence and Robotics Technology."

"Enable Significant Level of Automation of Ground, Flight and Space Operations for Streamlined Vehicle Processing and Logistics."

SPACE STATION:

"While advancement in all disciplines will be important to expand functional capabilities, automation and robotics will need to be emphasized as key to increasing human productivity and safety."

"Demonstrate Telerobotic Capability for Space Station Operations Applications."

"Develop Advanced Automation and Telerobotics for Vehicle/Element Assembly, Processing and Proximity Operations."

EXPLORATION:

"Enable Highly-Reliable, Cost Effective Space-Based Operations of Exploration Vehicles through Semi-Automated Vehicle Inspection and Serving and Automated Check-Out and Test of Vehicle Systems."

"Enable Long-Range, Piloted and Semi-Autonomous Mobile Surface Systems for Exploration, Transportation, and other Operations on the Lunar/Mars Surface."

"Enable Safe and Efficient Design of Exploration Human Automation-Robotics Systems, Including Human-Machine Interfaces."

"Enable Extensive, Cost-Effective Applications of Artificial Intelligence and Robotics for Planetary Surface Systems (Including both Science and Operations Systems)."

BREAKTHROUGH:

"Augment Human Physical Capability with Human-Manipulated Machines."

> "Enable Revolutionary Mission Capabilities with Supervised Autonomous, Mobile Robots."

Thus, the potential benefits to be realized by enhanced automation of NASA ground based operations are widely understood, and the importance of unmanned intelligent, or automated operations in space has been keenly recognized. Many of these operations could benefit from the application of dexterous robotic end-effectors.

5.2.2 U.S. Department of Energy Office of Environmental Restoration and Waste Management

The U.S. Department of Energy (DOE) Office of Environmental Restoration and Waste Management has announced a 30-year program aimed at restoring several national laboratory sites contaminated with toxic chemicals and high and low-level radioactive waste. In this regard, the February 1992 issue of ASME NEWS [5.3] reported that DOE will evaluate the role that mobile robots and other remote-controlled technologies can play in the clean-up. The report states that, "$820 million has been earmarked to implement robotics, including $220 million for development projects." However, some DOE researchers contacted during this study expressed the opinion that these figures may be inflated with actual totals targeted at $10, $18 and $24 million for 1991, 1992 and 1993 respectively.

Nevertheless, the DOE Office of Environmental Restoration and Waste Management Office of Technology Development has published a comprehensive, three-volume, five-year plan [5.4] entitled, "Environmental Restoration and Waste Management Robotics Technology Development Program Robotics 5-Year Program Plan." Copies of the plan, which addresses the period from FY 1991 through 1995, are available from the National Technical Information Services (NTIS). The 5-year plan discusses the overall approach to be adopted by DOE to aggressively develop robotics technology and contains discussions of the Program Management Plan, Site Visit and Needs Summary, Approach to Needs-Directed Technical Development, Application-Specific Technical Development, and Cross-Cutting and Advanced Technology. The report not only deals with potential benefits (faster, safer, cheaper) of robotics over the targeted five-year period, but identifies areas where longer-term research in robotics will have a high payoff in the 5- to 20-year time frame. The desired benefits are specified as follows:

Safer - Reduced worker exposure and increased safety through remote operation and control of equipment.

Faster - Increased speed and productivity for operations through enhanced capabilities and automation.

Cheaper - Faster, more productive systems resulting in quicker completion of remediation operations that in turn reduces life-cycle costs.

The plan is based on the needs identified at five DOE sites: Fernald, Hanford, Idaho, Rocky Flats, and Savannah River. Six major, cross-cutting environmental restoration and waste management applications which are of immediate importance and priority to DOE have been identified to focus the five-year initiative. These applications are: (1) Waste Storage Tanks (above ground and underground); (2) Buried Waste Retrieval; (3) Contaminant Analysis Automation; (4) Waste Minimization; (5) Decontamination and Decommissioning, and; (6) Waste Facilities Operations.

Contacts with managers and researchers involved with implementation of the five-year plan suggested that end- effectors of diverse size and dexterity might be required. A number of DOE researchers indicated that the requirements are still being studied. A list of key robotics coordinators follows:

Linton W. Yarbrough, Ph.D.
U.S. Department of EnergY
Robotics Program Manager
12800 Middlebrook Road
Trevison II/Suite 400
Germantown, MD 20874
(301) 353-7291/3

James Yount
Westinghouse - Hanford
LO-18 P.O. Box 1970
Richland, WA 99352
(509) 376-3284

Patrick J. Eicker
Sandia National Laboratories
Department 1410
P.O. Box 5800
1515 Eubank SE
Albuquerque, NM 87165
(505) 646-6329

David L. Jacoboski
Westinghouse
P.O. Box 398704
Cincinnati, OH 45239-8704
(513) 738-8986

Brad E. Griebenow
EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415-3930
(208) 526-0501

William R. Hamel, Ph.D.
D&D Coordinator
Oak Ridge National Lab.
P.O. Box 2008, Building 7601
Oak Ridge, TN 37831-6304
(615) 574-5691

Guy A. Armantrout
WM Coordinator
Lawrence Livermore National
Laboratory
P.O. Box 808 L-440
Livermore, CA 94550
(415) 422-1594

Clyde R. Ward
Westinghouse Savannah River
Company
Building 773-A, D1134
Aiken, SC 29808
(803) 725-5891

Two documents published by Sandia National Laboratories [5.5, 5.6] provide abstracts of research involving grasp planning, manipulation and perception, robotic handling of large heavy objects, force controlled manipulation, force reflecting telerobotics and torque control of robots. A Sandia technical contact concerning this work is the following:

Mr. Sig Thunborg
Sandia National Laboratory
Division 1414
Box 5800
Albuquerque, NM 87185
(505-844-3733)

5.2.3 U.S. Department of Energy Morgantown Energy Technology Center

The U.S. DOE Bureau of Mines Morgantown Technology Center in Morgantown, West Virginia published a Program Research and Development Announcement (PRDA) in August 1991 [5.7] soliciting proposals for "Research and Development for Environmental Restoration and Waste management Technologies." Closing date for submissions was December 13, 1991.

One of four major areas of research solicited by the PRDA was "Robotic Operations." In particular new technology development using robotics and automation to carry on process control to reduce human exposure to contaminants was sought. Sampling, handling and analyzing complex waste streams and radioactive, explosive, explosive-bearing, and/or mixed waste samples were specific areas of concern. Research in the following areas was targeted:

- Remote Controlled Removal Devices
- Enhanced Intelligence Robotics
- Long-Reach Robotic Manipulator Test Bed
- Interactive Computer-Enhanced Remote Viewing Systems
- Mobile Manipulation System

Specific requirements included flexible long reach manipulators with 6-to-7 degrees of freedom capable of manipulating payloads of approximately 1,200 kilograms and a mobile system with dexterous manipulation capabilities to handle objects and tools simultaneously. The portion of the PRDA describing the Robotic Operations Research Area has been excerpted in whole and is given in Appendix XX. The contact for the PRDA was the following:

Attn: Thomas L. Martin
U.S. Department of Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, WV 26507-0880

5.2.4 U.S. Department of Energy U.S. Bureau of Mines Pittsburgh Research Center

The Electrical & Electronics group of the U.S. DOE Bureau of Mines Pittsburgh Research Center is undergoing an intensive, systematic study to determine the potential for the development of new mining systems that will rely primarily on robotics technology to increase safety and production. In underground coal mining, the physical environment is characterized by unsafe and unpredictable conditions: roof falls, explosive methane gas, dust humidity, temperature, dampness, darkness, and confinement. The application of robotics technology to underground mining has the potential for improving mining systems and operations and reducing or eliminating the inherent hazards associated with mining operations.

The goal of the effort is for the Bureau of Mines to serve as a catalyst to increase the growth of robotics in mining. The Bureau is striving to provide the driving force during the early stages of research to identify new technologies that might significantly improve minerals production, processing and safety. It is attempting to expose new mining concepts and machine designs for comment and critique; to demonstrate a kind of system thinking that is appropriate; and to stimulate others to undertake and contribute similar, creative thinking in search of the best systems for the future. As the research matures and potential in mining is proven, the effort should become self-sustaining with industry assuming a major share of the support for continued research and development.

Current work at the Pittsburgh Research Center includes the development of a three-dimensional graphic simulation of mining scenarios for characterizing new mining methods and concepts. It is anticipated that the model will assist in establishing research priorities, assessing candidate robotic mining systems, identifying gaps in technology and economic constraints, and determining acceptability to the mining industry. A research contact at the Pittsburgh Research Center is the following:

Darryl Esprit
DOI/PRC/BOM/E&ES
Cochrans Mill Road
P.O. Box 18070
Pittsburgh, Pennsylvania 15236
(412) 892-6473

5.2.5 U.S. Air Force Wright Laboratory Flight Dynamics Directorate

In October 1988, Battelle completed a study for the Flight Dynamics Laboratory entitled, "Robotic Concepts for Aircraft Turnaround [5.8]." The objective of the study was to explore concepts for exploiting robotic system developments to perform aircraft turnaround functions in a chemical-biological environment and identify concepts to best meet Air Force objectives for increased efficiency with reduced personnel. The scope of the investigation included feasibility analyses relative to quick aircraft inspection, refueling and other systems replenishing, and munitions loading and rearming. The study was followed by scale model laboratory feasibility tests at the Flight Dynamics Directorate to investigate the concept of vision guided robotics to help implement various aspects of the automation.

The effort is continuing with work currently being performed to develop a related full-sized prototype system to further demonstrate the possibility of automated refueling. Possible future applications include not only military aircraft, but the National Aerospace Plane (NASP), and eventually commercial airliners. This work entitled, "Autonomous Robotics Refueling System (ARRS) [5.9]," is being performed under the guidance of Flight Dynamics project engineer, Keith Powell (513-257-7804/2129) by the following prime contractor:

International Submarine Engineering
1734 Broadway St.
Port Quitlam
British Columbia, Canada VC3-2M8

Another study conducted by the Flight Dynamics Directorate which may produce spin-off technologies applicable to NASA KSC ground based operations was entitled, "Advanced Theater Transport (ATT) Cargo Handling Study [5.10]." A follow-up to this initial effort is now underway with a cooperative effort by McDonnell Douglas, Lockheed and Boeing and with participation by

Germany and France. Flight Dynamics project engineer is Mr. David Perez (513-255-2129).

5.2.6 U.S. Air Force Wright Laboratory Manufacturing Technology Directorate

Work supported by the Manufacturing Technology Directorate includes the development of an automated system for paint stripping and de-riveting. Contractors for this work were the Southwest Research Institute (Contact: Mr. Robert Hambright, 512-522-2623) and The LTV Corporation (Contact: G. M. Engle, 214-266-2543). The system includes a five-axis unit that drills and fastens large, highly contoured composite B-2 aircraft parts to aluminum or titanium substructures.

To date two units have been placed into operation: one at Hill AFB, Ogden, Utah, and one at Warner Robbins AFB, Robbins, Georgia. LTV reports that the system has installed 50,000 fasteners, improved fastening quality by more than 90% over manual methods, decreased production time, and provided a 35% reduction in manual labor. By utilizing multiple function tool heads, drilling, fastening, and sealing can be done in one pass. The process uses coolant feeding drills and 750 psi (5.2 MPa) gaseous nitrogen to flush away chips, so the robot can drill and finish a hole in one pass. The system's adaptive control allows the robot to follow an ideal master part program and react to assembly irregularities. A camera and laser arrangement provides feedback.

Currently, a second generation system is under development by a Pratt and Whitney subsidiary of United Technology Corporation. the Manufacturing Technology Directorate project engineer is Mr. David See (513-255-2413).

Some of the technology associated with these Air Force projects may be applicable to the NASA funded $500,000 effort at Carnegie Mellon University's Field Robotics Center (Pittsburgh) to design and build a mobile robot to perform inspection and maintenance operations on the tiles covering the Space Shuttle. Mr. Kevin Dowling (412-268-8830) is a technical contact at Carnegie Mellon University.

5.2.7 U.S. Air Force Wright Laboratory Armstrong Aeromedical Research Laboratory and Air Force Institute of Technology

The Armstrong Aeromedical Research Laboratory of the Wright Laboratory and the Air Force Institute of Technology have conducted considerable research with regard to dexterous robotic hands. Previous work includes testing of the Utah-MIT Hand [5.11] in conjunction with the VPL DataGlove and investigations of force/torque feedback. Studies have been carried out using a force reflecting exoskeleton. In general, emphasis has been on telerobotic man-machine interface considerations and the effect of the human in the control loop [5.12, 5.13]. Work on the application of artificial neural networks (ANN) to assist in the implementation of master-slave control algorithms has been carried out. Captain Ronald G. Julian (513-255-3671) is a technical contact in the Aeromedical Research Laboratory.

5.2.8 National Science Foundation

The National Science Foundation Robotics and Machine Intelligence Program, headed by Dr. Howard Moraff (202-357-9586) funds some dexterous robotic hand research. However, according to Dr. Moraff, this type of research is not a priority at the present. The agency presently has more interest in simpler manipulators and specialized end-effectors and believes the usefulness of multi-fingered hands will not be near-term. Key researchers presently receiving NSF support for research related to robotic hands include the following individuals:

John Holerbach - Utah University
Rod Grupen - University of Massachusetts (508-545-3280)
Rich Weiss - University of Massachusetts (508-545-1975)
Josip Loncaric - University of Maryland (301-405-6626)
Roger Brockett - Harvard University (617-496-8359)
Ruzena Bajcsy - University of Pennsylvania (215-898-0370)

5.2.9 Federal Aviation Administration

Contacts with researchers at the Federal Aviation Administration indicate that to date little emphasis has been placed on the application of robotics for aircraft servicing, inspection, etc. One contact (John Fabry, 609-484-6132) reported that some related work is being done on non-destructive inspection.

5.2.10 Army Research Office (ARO)

The Army Research Office has provided support for robotics research involving dexterous robotics through grants and contracts to universities and industrial firms. Work has been supported at the Massachusetts Institute of Technology, Carnegie Mellon University and Utah University. The development of the SARCOS Arm and the Odetics Hand received ARO support. ARO support has also helped provide a 4800-pound payload robot at Martin Marietta in Baltimore. The device is being used to carry out research on highly instrumented grippers for ammunitions loading and unloading applications. Work is also being done on the first tactical robot. A previous emphasis on kinematics and mechanism studies is being phased out. An ARO technical contact is the following:

Director
U.S. Army Laboratory Command
Human Engineering Laboratory
ATTN: SLCHE-CE (Mr. John Stephens)
Aberdeen Proving Grounds, MD 21005-5001
(301-278-5870)

A February 1992 report available from Mr. Stephens' office [5.14] gives abstracts of several current robotics related initiatives under the direction of the ARO Human Engineering Laboratory (HEL). Included is a summary of "International Robotics Activities" involving formal technical exchanges with Canada, France and Germany and concerning common message protocol requirements for communication between control centers and robotic vehicles. Agreements with other countries are being actively considered and the possibility of technology transfer from Japan is being explored. A NATO workshop on Critical Operator-Robot Interaction Issues will be held in October 1992 with a HEL staffer serving as chairman. The point of contact is Dr. David Hodge at (301)-278-5865.

ARO is also involved in the following initiatives for automated materials handling:

Material Handling Equipment Enhancement Program (MHEEP)
Materials Handling Research Test Bed(MHRT)
DOD Robotics Testbed Program
HEL Enhancements to the S-EOD Robot
Mobile Manipulator (MoMan) Research Testbed

The MoMan effort in particular has a strong emphasis on tasks requiring dexterous manipulation. It involves a light weight high performance robotic manipulator aboard a telerobotic vehicle, controlled by a remote operator control unit. The Department of Energy Office of Technology Development is also investigating the use of this system for hazardous waste cleanup. DOE researchers have integrated a variety of subsurface imaging sensors onto the MoMan to assess their applicability to characterization of landfill waste storage sites and demonstrated the results in August 1991 at DOE's Idaho National Engineering Laboratory. The first capability for manipulation, built by Odetics under SBIR funding, was integrated by Oak Ridge National Laboratory (ONRL) in FY90. The first capability for true dexterous manipulation is being developed by Sarcos Research Corporation under SBIR funding. The point of contact for this effort is Maj. Harry McClellan at (301)-278-5895.

5.2.11 Office of Naval Research (ONR)

The Office of Naval Research is currently supporting robotics related research and development activities at the Woods Hole Oceanographic Institute in Falmouth, Massachusetts and at the Massachusetts Institute of Technology. Researchers at Woods Hole include Steve Ramberg and Dan Yoerger (508-548-1400). The supported research includes studies of tactile and touch sensing applicable to dexterous grippers. Following is a technical point of contact at ONR:

Ms. Teresa McMullen
ONR Code 1133
800 Quincy St.
Arlington, VA 22217
(703-696-3163)

5.2.12 Woods Hole Oceanographic Institute

The Woods Hole Oceanographic Institute has been involved with teleoperated robotics involving dexterous robotic end-effectors for underwater applications. A technical point of contact is Mr. Nathan Ulrich:

Mr. Nathan Ulrich
Deep Submergence Laboratory & Center for Marine Exploration
Woods Hole Oceanographic Institution
Woods Hole, MA 02543
(508-548-1400)

One of the dexterous hands being considered for applications at Woods Hole is the Penn Hand [5.15] which Mr. Ulrich helped develop at the University of Pennsylvania.

5.2.13 U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL)

The Construction Engineering Research Laboratory in Champaign, Illinois has a growing interest in the application of robotics for construction related operations. A technical contact at CERL is the following:

Major Thomas Kelley
Attn: CECER-EMS
Construction Engineering Research Laboratory
P.O. Box 9005
Champaign, IL 61826-9005
(800-USA-CERL)

CERL has tracked construction related robotics efforts at various universities and provided the following contacts in this regard:

Thomas Gatton - University of Texas-Austin (512-471-7862)
James O'Connor - University of Texas-Austin (512-471-4645)
Al Traver - University of Texas-Austin (512-471-3059)
Kevin Dowling - Carnegie Mellon University (412-268-8830)
Jackson Yang - University of Maryland (301-405-5306)

Other key research contacts include the following:

Red Wittaker
Redzone Robotics, Inc.
2425 Liberty Avenue
Pittsburgh, PA 15222-4639

Mr. Sam Shin
Construction Industry Institute (CII)
3208 Red River - Suite 300
Austin, TX 78705

Another source of updated information is the International Symposium on Automation and Robotics in Construction. The symposium which is held at various sites around the world is scheduled to convene in Japan in 1992 and in Houston, Texas in 1993. Indications are that the Japanese are investing heavily in technologies for automating construction operations and have gained a substantial lead in this technology. Some of the Japanese developments are reported in a CERL Technical Report entitled, "Automation and Robotics in Construction: Japanese Research and Development [5.16]."

5.3 Dexterous Robotic End Effector Survey

Previous literature searches have indicated that relatively little effort has been directed toward the development of robotic hand devices. Nevertheless, there are indications that broad commercial applications await the development of a reliable and safe, powerful, dexterous robotic hand device. It appears that such a device accurately controlled in a master/slave mode by an operator wearing an instrumented glove would be specially suitable for a number of operations that might find use in the KSC Shuttle preparation operations. Therefore, a survey was sent to industries, Government agences, military organization, universities and research institutes, etc. to determine the current or future need of robotic hand devices.

5.3.1 Objectives

The first objective of the survey was to determine those segments of the commercial market in which applications, or potential future applications of dexterous robotic hands exist.

Manufacturing/Process
- Assembly Operations
- Materials Handling/Machine Loading/Packaging
- Welding, Painting, Deburring, Etc.
- Inspection

Fright Shipping and Handling
- Packing/Palletizing
- Freight Handling (loading/unloading)
- Sorting

Construction
- Loading/Unloading
- Installation/Positioning
- Pouring Operations

Agricultural/Mining
- Planting/Harvesting, Mining
- Materials Handling
- Equipment/Facilities Servicing

Hazardous Operations

Toxic/Nuclear Waste Handling or Cleanup
Explosive Materials/Demolition Operations
Electrical Power
Very High/Low Temperature Operations
Fire Fighting, Crash Rescue, Etc.

Vehicle Maintenance (Airliners, Trucks, Ships, Military, etc.)

Servicing, Refueling, Rearming, Etc.
Cleaning, Painting
Inspection

Entertainment/Advertisement

Character Animation
Novel Displays
Cinema Special Effects
Demonstrations

The second objective was to determine specific processing functions, commonly done by human hand, in the for which potential gains are feasible by using such robotic devices. These processing functions include:

Inspect: Tasks in which the end effector may be required to maneuver the part or measuring equipment in order to examine structures or components with regard to predefined characteristics

Clean: Washing and/or removal of unwanted debris, sealants, coatings, contaminants, etc. from structures or objects in which the end effector may wield one or more devices such as spray nozzles, vacuum hoses, buffers, etc.

Connect/Disconnect, Assemble/Disassemble: Joining and/or removal of components according to predefined configurations where the end effector will affix, hold, clamp, etc. the pieces into position

Smart Crane Operations: Movement or lifting of heavy or large objects which may involve variable grasping actions or special positioning requirements

Cover/Uncover: Tasks where protective envelopes are placed/removed or fastened/unfastened on/from objects

Transport/Align: Tasks in which items are positioned with respect to predefined settings or features

Application/Welding: Application of paint, coatings, sealants, welds, etc. where the end effector may be required to manipulate one or more applicators such as spray nozzles, caulking guns, etc

The third objective of the survey was to determine which specific operational gains are most desirable. This will give an indication of potential benefits and the possibility of achieving these benefits for the various applications using robotic hand devices. For this purpose, the following operation criteria was used to evaluate potential benefits:

Operational Man Hours: The reduction or elimination of manual labor through the use of dexterous end effectors.

Flow Time: Reductions in individual cycle times or the overall process flow time.

Facility Modification: The amount of equipment additions and facility adjustments needed to properly implement a dexterous end effector.

Improved Safety: Improved safety factors and reduction or elimination of potential hazards through the utilization of a dexterous end effector.

Task Repetitiveness: Relates to how many times the task occurs in the mission. The more frequently a task occurs during processing, the greater the potential for achieving automation gains.

Human Limitations: Level of difficulty a human has performing a task well with respect to accuracy, speed, operating environment, etc. The more difficulty a human has performing a task, the easier it is to achieve automation gains through dexterous robotic hand application.

Task Improvement: Anticipated process improvement resulting from the potential automation of a processing task. Process improvements would include factors such as improved cleanliness through the reduction or elimination of human contamination, and reduced cost resulting from more accurate and efficient measurement or use of materials.

Probability of Automation Mishap: The probability that an accident or mishap will occur during the process as a result of the automation. The higher the probability, the harder it is to achieve automation gains.

Reliability Tolerance: The probability that a failure of a dexterous robotic hand would impact scheduled completion of a given processing task. The lower the probability of such impact, the easier it is to achieve automation gains.

Maintainability: Anticipated level of effort required to perform regular maintenance activities on a dexterous robotic hand. High maintenance efforts and the time required to perform them could impact scheduled completion of a given processing task. This might indicate difficulty in achieving automation gains and a poor automation candidate.

The fourth objective of the survey was to determine the specific configuration and performance requirements for different industrial applications. This would give an indication of specific technology or additional development. It will also determine the most needed types of robots and features. These performance requirements include:

Payload: The amount of mass the dexterous end effector must hold or support to perform a specific task. This requirement will help determine the overall dimensions, weight and performance characteristics of a dexterous hand necessary to perform its assigned task(s).

Work Envelope: This refers to the approximate volume of space that the dexterous unit has to reach, with all orientations, in order to perform a given task efficiently.

Precision: This refers to how closely a robot can return to the same position in the work envelope when given the same positioning command repeatedly.

Accuracy: This refers to how closely a robot can move to any specified position in the work envelope when commanded to move to that specific position.

Grasping Effort: This requirement reflects the level of effort required by a dexterous robot hand to adequately grasp and manipulate objects used in the performance of a given task.

Sensor Requirements: This involves the number and complexity of sensors associated with the successful performance of a specified task.

Visual Perception: This refers to the complexity of visual perception capabilities required by the dexterous robot to perform a task.

To meet our objectives the survey considered the following specific topics:

Application Information For Dexterous Automation
Generic Dexterous Processing Functions
Operational Criteria
Performance Requirements

A copy of the survey can be found in Appendix C.1

5.3.2 Scope

The survey covered a six month period from November 1991 to April 1992. It provided information about the current and anticipated future applications of robotic hand devices obtained from different organizations categorized as follows: Commercial/Industrial, Government other than Military, Military, Universities and Research Institutes. Four hundred and seventeen surveys were mailed and distributed across the organizations as follows:

213	commercial and industry
55	government other than military
35	military organizations, and
114	universities and research institutes

5.3.3 Implementation

In preparation of survey mailing, a long list of organizations was compiled from several sources: scientific journals, research publications, Thomas Register reference, personal contacts, conferences, factory referrals, industrial flyers, etc. This initial list was refined by screening phone calls to selected organizations coverings all the different categories attempting to get specific individual contact: Over 145 telephone calls were placed to find out which organizations may be using dexterous end effectors. These include: different manufacturers, Department of Energy Atomic Nuclear Operations, Bureau of Mines, USAF Flight Dynamics Directorate, USAF Manufacturing Technology Directorate, Defense Advanced Research Project Agency (DARPA), U.S. Army Corps of Engineers, National Institute of Standards and Technology (NIST), Construction Industry Institute (CII), Federal Aviation Administration (FAA), SANDIA National Lab., Hitachi, ODETICS, FML Corporation, Wright Patterson Air Force Base (WPAFB), Office of Naval Research, Department of Transportation (DOT), Department of Commerce, National Science Foundation (NSF), and others. Ninty-three surveys were sent to those organizations that responded favorably during the initial screening telephone conversation. To build on the initial mailing, 114 surveys were sent to different research institutes, universities and laboratories around the country and worldwide. Fifty-nine individuals among these organizations were personally contacted. Following this mailing step, 210 more surveys were sent to other organizations. A list of contacts can be found in Appendix C.2

The survey was twelve pages long and contained an introduction describing its objectives. To increase the possibility of responding, partially completed responses were welcomed in cases where requested information was considered proprietary; where portions of the survey were irrelevant to their specific application; or where certain requested data could not be properly examined.

To further increase the response, respondents were invited to request a copy of the survey results and/or final report. Furthermore, a stamped/addressed envelope was provided to return the completed survey forms.

5.2.4 Summary of Results

The response to these surveys by mail to these organizations was about 11% with 44 responses returned. Twenty-five of the 44 responses received were from universities and research institutes, 12 were from manufactures and distributors, and 5 from government other than military.

The CSU GRASP study team collected the survey responses and analyzed their results according to the four categories mentioned in the survey objectives. The following is a summary of the results and the procedure used in analyzing them.

A. Application Information for Dexterous Automation:

Some of the returned surveys reported more than one application in their organizations. The total number of the reported applications was calculated; and another for each operation within each application. A percent representing the ratio of the number of each application area with respect to the total number of application areas was calculated. Different operations within each application area were reported. Another percentage, for each operation, representing the weight of each operation relative to the others within the same application area was calculated. Table 5.1 includes these results for current applications and Table 5.2 for the potential future ones in a descending order. Important parameters and factors that indicate the present use of robotics and dexterous end effectors in automation with estimations of these factors for future implementation are

The average percent of all operations within the surveyed organizations that,

Are presently automated is	40%
Anticipated to be automated within one year is	24%
Anticipate will be automated within 2-to-5 years is	30%

The average number of robots in the surveyed operations that,

Are presently used is	8
Anticipated to be used within one year is	14
Anticipated to be used within 2-to-5 years is	20

The average number of dexterous robotic end effectors or robotic hands within the surveyed organizations that,

Are presently in use is	6
Anticipated to be in use within one year is	8
Anticipated to be in use within 2-to-5 years is	10

For dexterous operations currently performed in the surveyed organizations, the average value of

Total number of labor hours used monthly is	6046
Potential payoff (i.e. total dollar savings) for a 10% reduction in labor due to the use of automated systems is	25%
Potential payoff (i.e. total dollar savings) for a 30% reduction in labor due to the use of automated systems is	40%

Application Area	% of Applications	Operation	% of Operations
Manufacturing/ Process	45%	Assembly Operations	37%
		Material handling	26%
		Inspection	21%
		Welding, Painting, Debarring	16%
Fright Shipping and Handling	15%	Packing, Palletizing	46%
		Loading, Unloading	23%
		Sorting	31%
Hazardous Operations	14%	Toxic/Nuclear Waste Handling	36%
		Explosive Materials and Demolition Operations	23%
		Very High/Low Temperature	23%
		Electrical Power	18%
Vehicle Maintenance	9%	Cleaning, Painting	53%
		Inspection	27%
		Servicing, Refueling	20%
Construction	8%	Installation/Positioning	50%
		Loading/Unloading	36%
		Pouring Operations	14%
Agricultural/ Mining	8%	Materials Handling	42%
		Planting, Mining	36%
		Equipment/Facilities	22%
Entertainment/ Advertising	4%	Novel Displays	43%
		Character Animation	29%
		Cinema Special Effects	14%
		Demonstrations	14%

Table 5.1 Survey Results for Current Operations

Application Area	% of Applications	Operation	% of Operations
Manufacturing Process	28%	Assembly Operations	35%
		Inspection	25%
		Welding, Painting, Debarring,	21%
		Material handling	19%
Fright Shipping and Handling	16%	Loading, Unloading	39%
		Packing, Palletizing	33%
		Sorting	28%
Hazardous Operations	14%	Toxic/Nuclear Waste Handling	44%
		Explosive Materials and Demolition Operations	31%
		Very High/Low Temperature	19%
		Electrical Power	6%
Entertainment/ Advertising	12%	Demonstrations	50%
		Novel Displays	25%
		Cinema Special Effects	16%
		Character Animation	9%
Agricultural/ Mining	11%	Materials Handling	50%
		Equipment/Facilities	35%
		Planting, Mining	15%
Construction	10%	Loading/Unloading	45%
		Pouring Operations	34%
		Installation/Positioning	21%
Vehicle Maintenance	9%	Inspection	50%
		Cleaning, Painting	30%
		Servicing, Refueling	20%

Table 5.2 Survey Results for Potential Future Operations

B. GENERIC DEXTEROUS PROCESSING FUNCTIONS:

This part seeks to ascertain the functional areas of dexterous end effectors where the greatest number of commercial applications lie. The functions were ranked according to their relative usefulness in a scale from 1-to-10 for each of the functions (1 indicates least useful and 10 most useful). Average values were calculated and tabulated in Table 5.3.

FUNCTION	DESCRIPTION	RANK
Connect/ Disconnect, Assemble/ Disassemble	Joining and/or removal of components according to predefined configurations where the end effector will affix, hold, clamp, etc. the pieces into position	10
Inspect	Tasks in which the end effector may be required to maneuver the part or measuring equipment in order to examine structures or components with regard to predefined characteristics	8
Application Welding	of paint, coatings, sealants, welds, etc. where the end effector may be required to manipulate one or more applicators such as spray nozzles, caulking guns, etc	7
Clean	Washing and/or removal of unwanted debris, sealants, coatings, contaminants, etc. from structures or objects in which the end effector may wield one or more devices such as spray nozzles, vacuum hoses, buffers, etc.	6
Transport/ Align	Tasks in which items are positioned with respect to predefined settings or features	4
Cover/ Uncover	Tasks where protective envelopes are placed/removed or fastened/unfastened on/from objects	4
Smart Crane Operations	Movement or lifting of heavy or large objects which may involve variable grasping actions or special positioning requirements	1

Table 5.3 Ranking of Dexterous Processing Functions

C. Operational Criteria

This section reports results that determine the desirable operational gains. It give an indication of potential benefits and the possibility of achieving these benefits for the various applications using robotic hand devices. Each operational criteria is ranked, according to the reported appropriate "importance", on a numerical scale from 1-to-10. The rating is an indication of how important the specific benefit is in the overall operation (i.e., relative magnitude of resultant benefits). Table 5.4 shows the average rating of the operation criteria among the returned surveys. They are presented in a descending order. For definition of terms refer to the survey instrument in Appendix C.1.

CRITERIA	RANK
Improved Safety	9
Task Repetitiveness	8
Task Improvement	7
Human Limitations	7
Maintainability	7
Flow Time	6
Reliability Tolerance	6
Operational Man Hour	5
Facility Modification	5
Probability of Automation Mishap	4

Table 5.4 Ranking of Operation Criteria

D. Performance Requirements

This section reports the returned information about specific dexterous end effector performance requirements and which of those requirements are the most common. Tables 5.5, 5.6, and 5.7 show reported values for each requirement corresponding to each application as they indicated in the returned surveys. Appendix C.1 contains definitions of performance requirements different terms.

Application	Payload	Work Envelop		Precision	Accuracy	Grasping Requirements								
University		Radius	Length			Max. Grasp	Min. Grasp	Torque	Force	Cycle Time	Contact Points	No. of Fingers	Finger Joints	Manipulation Required
Mechanical Assembly	100 lb	--	3-4 ft	.01-.0001 in	0.01 in	1-6 in	--	--	5-50 lbf	--	--	2	--	5
Inspection	50 lb	--	3 ft	0.01 in	0.01 in	6 in	--	--	50 lbf	--	--	2	--	4
Installation/Positioning	100 lb	--	50 ft	0.5 to 0.1 in	0.5-0.1 in	2 to 6 in	--	--	20-50 lbf	--	--	2 to 3	--	1
--	25 lb	5 ft	--	0.02 in	0.05 in	6 in	.01 in	30 lbf-in	50 lbf	--	3	3 to 5	3	4
--	--	1 m	1 m	0.1 m	0.5 m	--	--	--	--	--	--	--	--	--
Robotic Assembly	0.5 lb	--	--	0.1 mm	1.0 mm	--	--	--	--	--	--	--	--	--
Material Handling	1.0 lb	--	--	1.0 mm	1.0 mm	--	--	--	--	--	--	--	--	--
Inspection	.05 lb	--	--	0.1 mm	1.0 mm	--	--	--	--	--	--	--	--	--
Assembly	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Robots in instruction	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Robots in space	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Truss assembly in space	weightless	--	5 m	--	10 mm	varies	--	--	--	--	--	--	--	--
Research auto. assembly	0 to 2 kg	.25 m	--	2 mm	25 mm	10 cm	2 cm	5 N m	60 N	6 s	--	3 to 4	3 to 4	3
Sensory exploration	0 to 0.5 kg	1.0 m	--	10 mm	25 mm	10 cm	4 cm	.5 N m	1 N	--	--	3 to 4	3 to 4	1
Prep. plant material	.02 kg	0.5 m	--	0.2 mm	0.5 mm	1.5 cm	0.3 cm	--	10 N	120 s	2	--	--	4
Citrus harvesting	0.1 kg	1.0 m	--	1.0 mm	2.0 mm	10 cm	5 cm	--	--	60 s	3	--	--	2
Inspection/Positioning	--	--	--	--	--	7 cm	2 cm	--	10 N	5 s	3	3	3	5
Roll btween fingers	--	--	--	--	--	10 cm	1 cm	--	5 N	2 s	2	2	3.5	5
Inspection of parts	2 lb	--	1 m	.001 in	.001 in	6 in	0.5 in	--	--	--	2	2	--	3
Welding	5 lb	4 ft	--	.062 in	.062 in	--	--	--	--	--	--	--	--	--
Various Senses	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Put & place obj.	2.5 lb	6 ft	6 ft	.05 in	.05 in	4 in	.25 in	150 lbf-in	10 lbf	--	--	2	0	3
Assembly	2.0 lb	5 ft	6 ft	.05 in	.05 in	4 in	.25 in	100 lbf-in	18 lbf	--	--	2	0	4
Inspection	1.0 lb	3 ft	6 ft	.05 in	.05 in	4 in	.25 in	100lbf-in	18 lbf	--	--	2	0	5
Shuttle tile service	25 kg	1.0 m	--	0.5 mm	1.0 mm	--	--	--	--	--	--	--	--	1
Remote excavation	100's kg	2.0 m	--	25 mm	50 mm	--	--	100's N	1000 N	--	--	--	--	3
Dexterous walking	1000's kg	N/A	--	N/A	N/A	--	--	--	1000 N	--	--	--	--	5

Table 5.5a Performance Requirements for Applications Within Universities

Application	Sensor Requirements										Vision Requirements								
University	Position	Velocity	Acc.	Force	Torque	Limit Switch	Pro-ximity	Tactile	CMM	Vision	B & W Camera	Color Camera	Photoelectric Sensors	Multiple Cameras	Gray Image	Binary Image	Range Image	Special Lighting	Special Filters
Mechanical Assembly	xxxx			xxxx			xxxx			xxxx		xxxx			xxxx			xxxx	
Inspection	xxxx			xxxx			xxxx				xxxx			xxxx	xxxx		xxxx	xxxx	
Installation/Positioning	xxxx	xxxx		xxxx	xxxx		xxxx	xxxx			xxxx		xxxx		xxxx				
--	xxxx	xxxx	xxxx	xxxx	xxxx		xxxx				xxxx		xxxx		xxxx	xxxx			
..	xxxx	xxxx		xxxx		xxxx	xxxx												
Robotic Assembly				xxxx															
Material Handling													xxxx						
Inspection											xxxx								
Assembly	xxxx			xxxx				xxxx											
Robots in instruction	xxxx			xxxx				xxxx											
Robots in space	xxxx			xxxx				xxxx											
Truss assembly in space	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx		xxxx		xxxx	xxxx						xxxx	xxxx	xxxx
Research auto. assembly	xxxx	xxxx			xxxx					xxxx	xxxx								
Sensory exploration	xxxx	xxxx			xxxx					xxxx	xxxx								
Prep. plant material	xxxx	xxxx		xxxx			xxxx			xxxx		xxxx							
Citrus harvesting	xxxx			xxxx			xxxx			xxxx		xxxx							
Inspection/Positioning				xxxx															
Roll btween fingers				xxxx															
Inspection of parts	xxxx							xxxx	xxxx		xxxx			xxxx					
Welding							xxxx			xxxx	xxxx				xxxx			xxxx	
Various Senses																			
Put & place obj.	N/A										N/A								
Assembly	N/A										N/A								
Inspection	N/A										N/A								
Shuttle tile service						xxxx	xxxx			xxxx	xxxx	xxxx							
Remote excavation	xxxx	xxxx	xxxx	xxxx	xxxx		xxxx					xxxx					xxxx		
Dexterous walking	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx							xxxx			xxxx		

Table 5.5b Sensor/Vision Requirements for Applications Within Universities

Application	Payload	Work Envelop		Precision	Accuracy	Grasping Requirements								
Industry		Radius	Length			Max. Grasp	Min. Grasp	Torque	Force	Cycle Time	Contact Points	No. of Fingers	Finger Joints	Manipulation Required
Material Handling	80-90 lb	4.3-7.9 f	--	.02 in	--	43 in	38 in	--	282 lbf	1-2 s	5	2	2	2
Manufacturing Valves	2 to 9 lb	--	--	--	--	--	--	--	--	--	--	--	--	--
Sealant Application	12 lb	--	--	1 mm	0.5 mm	6 in	.325 in	--	50 N	--	5	--	--	5
Robotic Spot Welding	100 lb	--	--	1 mm	0.5 mm	24 in	6 in	--	50 N	--	--	--	--	2
Gripper Force Controls	5 lb	--	--	--	0.5 mm	--	--	--	--	--	--	--	--	5
Material handling	500-600 lb	20-25 ft	10-15 ft	.25 in	.25 in	15-18 in	.125 in	unknown	200 lbf	1-2 s	2 to 3	2 to 3	1 to 2	3
Inspection	20-25 lb	5-10 ft	20-50 ft	.05 in	.01 in	4-5 in	.25 in	45-50 lbf-	100 lbf	1-2 s	2 to 3	2 to 3	1 to 2	4
Mating/Demating	25-150 lb	3-7 ft	2-5 ft	0.1 in	0.1 in	4-5 in	.125 in	varies	100-200 l	20-30 s	5 to 6	5 to 6	2 to 3	5
Small parts assembly	20 lb	3 ft	6 ft	.001 in	.005 in	10 in	0	--	25 lbf	0.4 s	3 min.	--	--	3
Environment Restor.	20-200 lb	--	--	--	--	--	--	--	--	--	--	--	--	--
Ammo. Handling	100 lb	--	--	--	--	--	--	--	--	--	--	--	--	--
Med. Prosthetics	20 lb	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 5.6a Performance Requirements for Applications Within Industry

Application	Sensor Requirements										Vision Requirements								
Industry	Position	Velocity	Acc.	Force	Torque	Limit Switch	Pro-ximity	Tactile	CMM	Vision	B & Camera	Color Camera	Photoelectric Sensors	Multiple Cameras	Gray Image	Binary Image	Range Image	Special Lighting	Special Filters
Material Handling																			
Manu. Valves																			
Sealant Application	xxxx	xxxx	xxxx				xxxx	xxxx		xxxx			xxxx						
Robotic Spot Welding	xxxx	xxxx		xxxx	xxxx	xxxx	xxxx												
Gripper Force Controls	xxxx	xxxx		xxxx	xxxx	xxxx	xxxx	xxxx											
Material handling	xxxx	xxxx		xxxx	xxxx	xxxx		xxxx		xxxx	xxxx								xxxx
Inspection	xxxx																xxxx		
Mating/Demating	xxxx			xxxx	xxxx	xxxx	xxxx	xxxx		xxxx				xxxx			xxxx		
Small parts assembly	xxxx			xxxx	xxxx	xxxx	xxxx	xxxx		xxxx	xxxx			xxxx	xxxx		xxxx	xxxx	
Environment Restor.								xxxx		xxxx	xxxx	xxxx		xxxx			xxxx		xxxx
Ammo. Handling								xxxx		xxxx	xxxx	xxxx		xxxx			xxxx	xxxx	xxxx
Med. Prosthetics								xxxx		xxxx									

Table 5.6b Sensor/Vision Requirements for Applications Within Industry

Application	Payload	Work Envelope		Precision	Accuracy	Grasping Requirements								
Government/ Military		Radius	Length			Max. Grasp	Min. Grasp	Torque	Force	Cycle Time	Contact Points	No. of Fingers	Finger Joints	Manipulation Required
Hazard Waste Clean-up	<=600 lb	<=20	--	10 mm	250 mm	varies	varies	varies	varies	--	--	--	--	--
Welding	N/A	--	--	0.1 in	N/A	N/A	--	--	--	N/A	--	N/A	--	2
Parts Loading	<2 lb	--	--	.01 in	N/A	--	--	--	--	--	--	2	--	2
Laboratory	5 lb	--	--	.01 in	.01 in	--	--	--	--	2 s	--	varies	--	3
Exper. Grasping Cup	10-20 lb	1 ft	1 ft	.005 in	.125 in	6 & 12 i	0.5 in	15 & 100	10-100 lb	1 s	2 to 3	--	--	1 to 2
--	30 lb	2 m	--	.004 in	.75 in	2 in	1 in	--	20 lbf	2 s	--	2	1	--
--	50 lb	2 m	--	.004 in	.75 in	4 in	1 in	--	10 lbf	20 s	--	2	1	--
Coating Application	--	7 ft	10 ft	.005 in	.005 in	--	--	--	--	--	--	--	--	--
Dexterous Assembly	10-15 lb	1.0 m	--	1-2 mm	5.0 mm	15 cm	.1 cm	--	--	--	--	3	2	5

Table 5.7a Performance Requirements for Applications Within Government and Military Organizations

Application	Sensor Requirements										Vision Requirements								
Government/ Military	Position	Velocity	Acc.	Force	Torque	Limit Switch	Pro-ximity	Tactile	CMM	Vision	B & Camera	Color Camera	Photoelectric Sensors	Multiple Cameras	Gray Image	Binary Image	Range Image	Special Lighting	Special Filters
Hazard Waste Clean-up	xxxx	xxxx		xxxx	xxxx	xxxx	xxxx	xxxx		xxxx	xxxx	xxxx						xxxx	xxxx
Welding																			
Parts Loading																			
Laboratory																			
Exper. Grasping Cup	xxxx					xxxx	xxxx				xxxx	xxxx	xxxx						
--	xxxx			xxxx	xxxx	xxxx	xxxx	xxxx		xxxx		xxxx						xxxx	
--	xxxx			xxxx	xxxx	xxxx	xxxx	xxxx		xxxx		xxxx							
Coating Application																			
Dexterous Assembly	xxxx	xxxx		xxxx	xxxx					xxxx	xxxx	xxxx		xxxx	xxxx				

Table 5.7b Sensor/Vision Requirements for Applications Within Government and Military Organizations

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CHAPTER 6

METHODOLOGY FOR ASSESSING GROUND PROCESSING APPLICATIONS

6.1 Introduction

The GRASP study team investigated applications of specialized end effectors for Space Shuttle ground processing operations performed at Kennedy Space Center (KSC). In order to accurately determine potential candidates for automation, the team developed a methodology to evaluate and rank the numerous ground processing operations performed at KSC. The results produced by this methodology were used to identify the operational task(s) that would yield the greatest benefits from the application of dexterous robotic hand technology.

The two phase methodology developed by the team was based on the approach and methodology developed for the Payload Processing System Study (PPSS), Reference [6.1]. The approach developed for the PPSS was used to evaluate and rank numerous payload processing tasks at KSC to determine suitable candidates for process improvements through robotics and automation. GRASP study team members, after careful review of the PPSS approach, used the same general method, but with some enhancements specifically designed to focus on dexterous robotic hands.

The methodology developed includes the following two steps:

1. Information gathering on ground processing operations
2. Task evaluation and ranking based on a specific set of criteria developed to determine attractive potential tasks

The first step involves the review of available documentation on various ground processing operations and a detailed examination of KSC ground processing facilities. Also during this first step, a comprehensive review of ground processing operations is performed by visiting Space Shuttle, payload, and expendable launch vehicle ground processing facilities at KSC. Detailed knowledge of specific processing operations is obtained through discussions

with NASA and contractor operations personnel. This information is then used to identify candidate tasks which might benefit from the application of automation. A preliminary list of ground processing tasks is generated, representing tasks which potentially would benefit from the application of dexterous robotic hand technology.

During the second step, the preliminary task list is evaluated in detail. This evaluation involves compiling more detailed task information, determining specific dexterous hand requirements, and numerically ranking all tasks for their automation potential. This ranking is based on providing numerical scores for a number of criteria. The criteria are arranged in two general groups representing the overall benefits of automating the task and the probability that an automated dexterous robotic system could be effectively implemented to perform the task.

6.2 Task Categories

Before performing the numerical ranking of the tasks, each of the tasks are placed into a general task category. A total of seven general categories were established after considering the overall list of potential tasks. Using these general categories allows for consistent and more rapidly applied scores. That is certain criteria receive a nearly equivalent score for all tasks within a specific category. The use of general categories also helps organize and delineate the technologies needed for each task. That is, the technologies needed are for the most part common to a specific category.

The categories developed were primarily based on the type of processing operations performed. These categories and a description of each are presented in Table 6.1.

TASK CATEGORIES	CATEGORY DESCRIPTIONS
Inspect	The tasks in which objects, parts, structures, and other components are examined against a set of predefined characteristics.
Clean	Tasks where unwanted contaminants, impurities, or foreign debris are removed from objects or structures.
Connect/Disconnect; Mate/Demate	Tasks involving the separation/removal or joining/insertion of components.
Crane Operations	Tasks where heavy objects are lifted and/or moved.
Cover/Uncover	Tasks where protective envelopes are placed/removed or fastened/unfastened on/from objects.
Transport/Align/Calibrate	Tasks where objects are positioned with respect to predefined settings/features.
Miscellaneous	Tasks not applicable to any of the above categories.

Table 6.1 Task Categories

6.3 Evaluation Methods

As mentioned above the first step in evaluating and ranking the tasks is compiling detailed information for each task. Once this is accomplished a numerical score is determined for a number of specific criteria for each task. In addition to this the specific technical requirements of a dexterous end-effector are generated for each task.

6.3.1 Information Compilation

Information gathered for the evaluation is grouped into five areas: (1) Operations Review, (2) Facilities, (3) Missions, (4) Technology, and (5) Other. Information in documentation form was obtained either through review of library material available at the NASA KSC Library, or in some cases, through reproduction of procedures documents for specific ground processing operations. Documents were collected, categorized and recorded in an electronic database for quick reference. Section 6.4 presents a complete list of documents used by the team during this stage of the study effort. The categories used for grouping acquired information are shown in Table 6.2.

In addition to reviewing various processing documentation, the study team utilized the expertise of NASA and contractor ground processing operations personnel in an effort to obtain more insight into all aspects of ground processing operations performed at KSC. Operations personnel provided tours of processing facilities and provided detailed explanations of processing operations. Operations personnel also played a key role in identifying particularly hazardous and manually difficult processing operations that might be good tasks for automation using dexterous robotic hand technology. The cooperation of NASA and contractor operations personnel throughout the study effort was instrumental in providing detailed information regarding operational procedures. Valuable assistance was provided by operations personnel by focusing the team's efforts on the potential automation of tasks which would provide substantial operational benefits, especially in areas such as hazardous operations and time-consuming tasks.

Operations Review	Information and collected documentation describing operations was grouped into this category. Primarily, this type of information was gained through visits to KSC facilities, discussions with contractor personnel directly involved in ground processing operations, NASA representatives and review of available operations concept documentation.
Facilities	Information grouped into this category describes tasks performed at specific KSC ground processing facilities. Information compilation in this category focused on obtaining documentation describing specific facility activities such as payload processing, vehicle preparation and refurbishment.
Missions	Information acquired and grouped into the 'Missions' category included documentation describing mission specific payload processing tasks, mission processing schedules and general payload processing planning information. This information included Payload Integration Plans (PIP's) and Launch Site Support Plans (LSSP's).
Technology	Information in this category includes general technical documentation describing technology and its implementation which has potential application for automation of ground processing tasks. This information included previously conducted studies, reports, proceedings, notes and textbooks.
Other	This category contained information that did not fall into any of the four primary categories, but still provided information useful to the study team.

Table 6.2 Information Areas

6.3.2 Evaluation Criteria

Two separate issues must be considered in evaluating which potential tasks are most attractive as automation applications. First the advantages or payback to be gained from replacing or reducing the amount of tasks performed by human technicians must be evaluated. Obviously those tasks which produce the most value when automated, based on the attitudes of operational personnel, are most attractive. Secondly, the technical issues associated with successfully implementing a dexterous, automated processing system must also be considered. A potential application is more attractive if it has a high probability of being successfully implemented. The criteria which address the task benefits are grouped into a set of operational criteria. The criteria which address the technical success issues are grouped into a set of technical criteria. The specific description of each of these criteria sets is provided below:

Technical	This category contains information which represents technical considerations of the task. This information was used to establish technical criteria; which were used to determine the feasibility that required technologies are/will be available to perform a given task.
Operational	This category contains information which represents operational considerations of the task. This information was used to establish operational criteria; which was used to determine the total operational impact of automation. Total operational impact was determined through a process of weighting the values assigned to these criteria for a given task.

Table 6.3 Criteria Description

The Operational Criteria used to evaluate tasks based on their benefit or impact from an operational standpoint, are presented in Table 6.4. Note each criterion has an associated weight. These weight are used to establish relative importance of each criteria within its set. The values of the weighting factors fall within a range between one and five; one being the lowest and five being the highest. These criteria are not presented in any specific order of importance.

CRITERIA	DESCRIPTION	WEIGHTS
OPERATIONAL MAN HOURS	Operational man hours (i.e. potential savings) which can be reduced or eliminated through robotic automation.	2
EXISTING FLOW TIME	How this task influences the serial time flow of the mission and also identifies the potential impact of robotic automation on processing flow time. Major flow time reductions due to automation are graded highly.	5
FACILITY MODIFICATION	The amount of facility modifications or equipment additions required to automate the task. Limited impacts will be graded or scored highly and major impacts will be scored with lower grades.	4
IMPROVED SAFETY	Factors and the potential personnel and hardware hazards which exist during task performance. It identifies hazardous operations such as fueling, ordnance installation/removal, installation/connection and lifting operations where operator exposure could be reduced or eliminated through the use of robotics.	5
TASK REPETITIVENESS	How many times the task occurs in the mission through the use of robotics. The more frequently a task occurs during processing, the better automation candidate it becomes and in general would rank higher.	3

Table 6.4 Operational Criteria

(continue on next page)

HUMAN LIMITATIONS	The difficulty a human has in performing a task well. It identifies tasks which exceed human capabilities, including strength, reach, access, fine resolution, dexterity, endurance, etc. The more difficulty a human has in performing a task, the better automation candidate it becomes and in general would rank higher.	2
TASK IMPROVEMENT	Anticipated process improvement resulting from the potential automation of a processing task. Process improvements include things such as improved cleanliness through the reduction or elimination of human contamination and reduced cost resulting from more accurate and efficient measurement and use of materials.	2
PROBABILITY OF MISHAP	The probability that an accident or mishap will occur during the process resulting from the application of automation to given processing task.	5
RELIABILITY TOLERANCE	The probability that dexterous robotic hand failure would impact scheduled completion of a given processing task.	5
MAINTAINABILITY	The anticipated level of effort required to perform regular maintenance activities on a dexterous robotic hand. High maintenance efforts and the time required could impact scheduled completion of a given processing task.	4

Table 6.4 Operational Criteria (continued)

The technological criteria and their relative weights are shown below in Table 6.5. These criteria are not presented here in any specific order of importance.

DESIGN TIME IN YEARS	Design time in number of years from detailed concept to prototype development and testing,
TECHNOLOGY AVAILABILITY AND MATURITY	The availability of critical technology required to automate a given task. If the technology is unavailable at the desired implementation time, then it becomes a major obstacle in automating a processing task.
TASK COMPLEXITY	This criterion considers for example the amount of sensor data, positional accuracy and path planning required to automate a task. Automation is obviously easier to apply to tasks with lower complexity.
TECHNOLOGY COST	The implementation costs of using technology to meet automation requirements.

Table 6.5 Technological Criteria

6.3.3 Developing Dexterous Hand Requirements

Dexterous robotic hands designed for performing ground processing operations must possess attributes which enable them to operate and adapt to the conditions encountered during ground processing operations at KSC. Dexterous robotic hand usefulness will depend on their ability to demonstrate a high degree of adaptability and flexibility. These characteristics must be considered during their design and development. In order to meet the demands of flexibility and robustness which would be imposed by KSC ground processing environments, designers will have to consider the specific demands of the operational environment encountered at various processing facilities.

Since many potential applications are in environments requiring various degrees of dexterity manipulating objects in a variety of sizes and weights, a close examination of the task ranking performed in this study provide important considerations for high level dexterous robotic hand design constraints.

Developing dexterous robotic hand design requirements relies on the identification of crucial parameters of a robotic system required to automate a specific task. Since there is clearly no general solution to the problem of designing a dexterous robotic hand, significant definition can be achieved by interpreting information

representing robotic system characteristics and capabilities required in the performance of a given task. The study team, using detailed processing operation information and generally available information on currently available robotic hand technology, established design constraints for a dexterous robotic hand suitable for automating a given task.

Each requirement in Table 6.6 provides a definition of the general capabilities and their resultant system design considerations for a dexterous robotic hand designed to perform a given task. These requirements, when used in conjunction with the results of a comprehensive study of potential applications to be automated, such as those performed in this study, provide the designer with a realistic baseline for the design and development of versatile, dexterous robotic hands.

6.3.4 Scoring Procedure

The actual task ranking is very straightforward. The approach is designed to isolate operational tasks which provide the most potential improvement through the application of dexterous robotic hand technology. Once all relevant available information regarding each task was analyzed, each task was entered into a spreadsheet. Numerical values for all operational and technological criteria were provided through a consensus of the study team members. Each score is then multiplied by the weight for that criterion resulting in a weighted score for each criterion. The weighted scores for all of the operational criteria are then summed resulting in a single operational based score for each task. The same is done for all of the technical criteria resulting in a single technical based score for each task. The entire task is then ranked based on the total of these two scores.

PAYLOAD	Total payload capacity required by a robotic hand to perform a given task. Payload capacity requirements help determine the overall size, geometry, weight and performance characteristics of a dexterous robotic hand necessary to perform a given task.
DEXTEROUS WORKSPACE (Work Envelope)	The volume of space which the robot end effector is required to reach while maintaining full 6 DOF motion in the performance of a given task. Dexterous workspace requirements will help determine the degrees of freedom, range of motion (translation) and effective reach requirements of a dexterous robotic hand necessary to perform a given task.
PRECISION	The precision or measure of accuracy with which a dexterous robotic hand can apply motions or forces to an object during task performance. A robotic hand grasping a part located with a vision system, for example, must be able to move to the Cartesian coordinates supplied to it by the vision system.
VISUAL PERCEPTION	The level of visual perception required to support a robotic hand performing a given task. A simple task would require basic visual perception capabilities and more complex tasks might require more visual perception sophistication.
SENSITIVITY (Sensor Requirements)	The sensitivity associated with successful performance of a given task. A task requiring the ability to detect small vibrations and small changes in force and position will require a robotic hand with more sensors than one required to detect large vibrations or large changes in force and position.
GRASPING EFFORT	The level of effort required by a dexterous robotic hand to adequately grasp and manipulate objects used in the performance of a given task. Objects used in task performance could include items such as tools or fasteners. Grasping effort requirements for task completion will help determine constraints on force closure, friction, torques and contact points for a dexterous robotic hand.

Table 6.6 Dexterous Robotic hand Design Requirements

6.4 References

6.1 NASA Payload Processing System Study, Final Report, October 1990

6.2 NASA SRB Disassembly Manual, DM No. B8001, Rev. Q

6.3 NASA SRB Systems Mate and Closeout, OM No. B5304, Rev. M

6.4 NASA ET Move and Mate SRB's, OMI No. S0003, Rev. W

6.5 NASA SSME Removal - Horizontal, OMI No. V5058, Rev. K

6.6 NASA RH APS POD Removal and Prep for Transport, OMI No. V5011.004, Rev. R

6.7 NASA Orbiter/ET Mate, OMI No. S0004, Rev. AE

6.8 NASA Upper Atmosphere Research Satellite (UARS), Launch Site Support Plan, May 1991

6.9 NASA Thermal Protection System Process Automation Study, Final Report, October 1990

9.10 Payload Canister Cleaning Robot, Proposed Initial Concept, Boeing, Aerospace Operations for Robotic Applications Development Laboratory, NASA-KSC

6.11 Automated Payload Canister Cleaning System, Facility and Equipment, Requirements Documentation, K-MMSE-10.1.5, MDSSC-KSC, July 1990

6.12 Technology Assessment of Robotic Hands, Final Report, October 1989, Central State University

CHAPTER 7
RESULTS OF NASA KSC GROUND PROCESSING APPLICATIONS ASSESSMENT

7.1 Overview of KSC On-Site Review

The Ground Robotic Hand Applications for the Space Program (GRASP) study effort investigated applications of specialized robotic end effectors for Space Shuttle ground processing operations performed at the Kennedy Space Center. A joint on-site operations review of ground processing tasks was completed in early August, with the entire study team participating. The on-site review provided a focused period of approximately two weeks for all GRASP team members to participate in a detailed examination of identified ground processing tasks. GRASP study team members were provided the opportunity to gain in-depth working knowledge of specific Space Shuttle ground processing operations. The GRASP team is extremely grateful for the valuable assistance of the numerous NASA and contractor operations personnel shown in Table 7.1. Their support in facilitating and conducting tours and the information they provided regarding ground processing operations enabled the study team to concentrate its efforts on facilities with the greatest potential for identifying tasks which would benefit from the application of dexterous robot hand automation.

Facilities visited by the GRASP study team during the on-site operations review included: the Operations and Checkout Building (O&C), Hangar AF, Orbiter Processing Facility (OPF), Assembly and Refurbishment Facility (ARF), Vehicle Assembly Building (VAB), Mobile Launch Platform (MLP), Rotation, Processing and Storage Facility (RPSF) and the Delta expendable vehicle Launch Complex.

Tours of some facilities, such as a the Payload Changeout Room (PCR) at the launch pad, were not possible due to an impending Shuttle launch. Time constraints prevented rescheduling of a PCR tour, however, MDSSC-KSC study team members have previously visited this facility and compiled information on processing operations.

Operations Personnel	Processing Facility	Affiliation
Mr. Wayne Rinow	VAB, RPSF	NASA
Mr. Tim Barth	OPF	NASA
Mr. Ford Hacker	Hangar AF	Thiokol Corporation
Mr. Art Glaab	O&C, Delta	MDSSC-KSC
Mr. Ken Flemming	OPF	MDSSC-KSC
Mr. Rick Vargo	PCR	MDSSC-KSC
Mr. Mike Secoda	OPF	Lockheed Space Operations
Mr Gary Henderson	ARF	United Technologies USBI.
Mr. Doug Keuneke	ARF	United Technologies USBI.

Table 7.1 Operations Personnel

7.2 Overview of KSC Ground Processing Operations

The Kennedy Space Center is the primary launch and landing site for the Space Transportation System (STS), more commonly referred to as the Space Shuttle. KSC is also the primary site for launching payloads on expendable vehicles such as the Delta rocket. Preparation, final checkout and loading of payloads into the Space Shuttle and expendable launch vehicles is also the responsibility of KSC.

Post mission processing operations performed at KSC include Shuttle post landing processing and deintegration of payloads.

Payloads received for processing are typically classified into either horizontal, vertical, mixed or special processing classifications. Incoming payloads are received at KSC by air, sea or land transportation. Processing of payloads for flight is performed in various KSC facilities depending on the type of payload and/or upper stage involved.

Before flying as part of an integrated payload, horizontal payloads such as Spacelab modules or pallet missions are processed as illustrated in Figure 7.1. Individual experiments or modules are received at the Operations and Checkout Building (O&C), where preliminary inspection, integration and testing processing operations are performed. The payload is then moved to the Orbiter Processing Facility (OPF), where it is integrated with the Space Shuttle Orbiter vehicle. After integration, the Orbiter with its payload is towed to the Vehicle Assembly Building (VAB) where mating with the external fuel tank and the solid rocket boosters is then performed. The integrated STS vehicle is finally transported to the launch pad on the Mobile Launch Platform (MLP), where final preflight processing operations are performed on the launch pad as required in the Payload Changeout Room (PCR). The PCR is part of the launch pad's Rotating Service Structure (RSS), a large, movable, gantry-like structure.

Vertical Payload processing operations are performed as illustrated in Figure 7.2. Specific processing flows vary depending on the type of payloads and/or upper stages involved. Payload elements, such as deployable satellites or satellite retrieval missions, are received at the Payload Processing Facility (PPF), where initial inspection, assembly and functional testing operations are performed. Once these operations have been completed, the vertical payload is transported either to the Vertical Processing Facility (VPF) or the Hazardous Processing Facility (HPF), depending on whether or not hazardous operations are required. After testing, the payload is transferred to the launch pad using the canister transporter, where it is loaded into the PCR of the RSS. The payload is then removed from the canister and placed in the Orbiter cargo bay, where Orbiter interface connection, verification testing, final checkout and servicing operations are performed prior to launch.

Mixed payloads, as illustrated in Figure 7.3, are a mixture of horizontally processed payloads which require integration with vertical payloads. Mixed payload arrival and receiving, preparation and staging processing, integration and testing processing and launch pad processing use various KSC processing facilities previously described depending on payload and/or upper stage type.

7.3 Preliminary Identification of Candidate Tasks

One of the first steps in performing the task evaluation was to compile a preliminary list of potential tasks which might benefit from the application of dexterous robot hand automation. Tasks for the study team's preliminary list were selected under the categories described in the previous

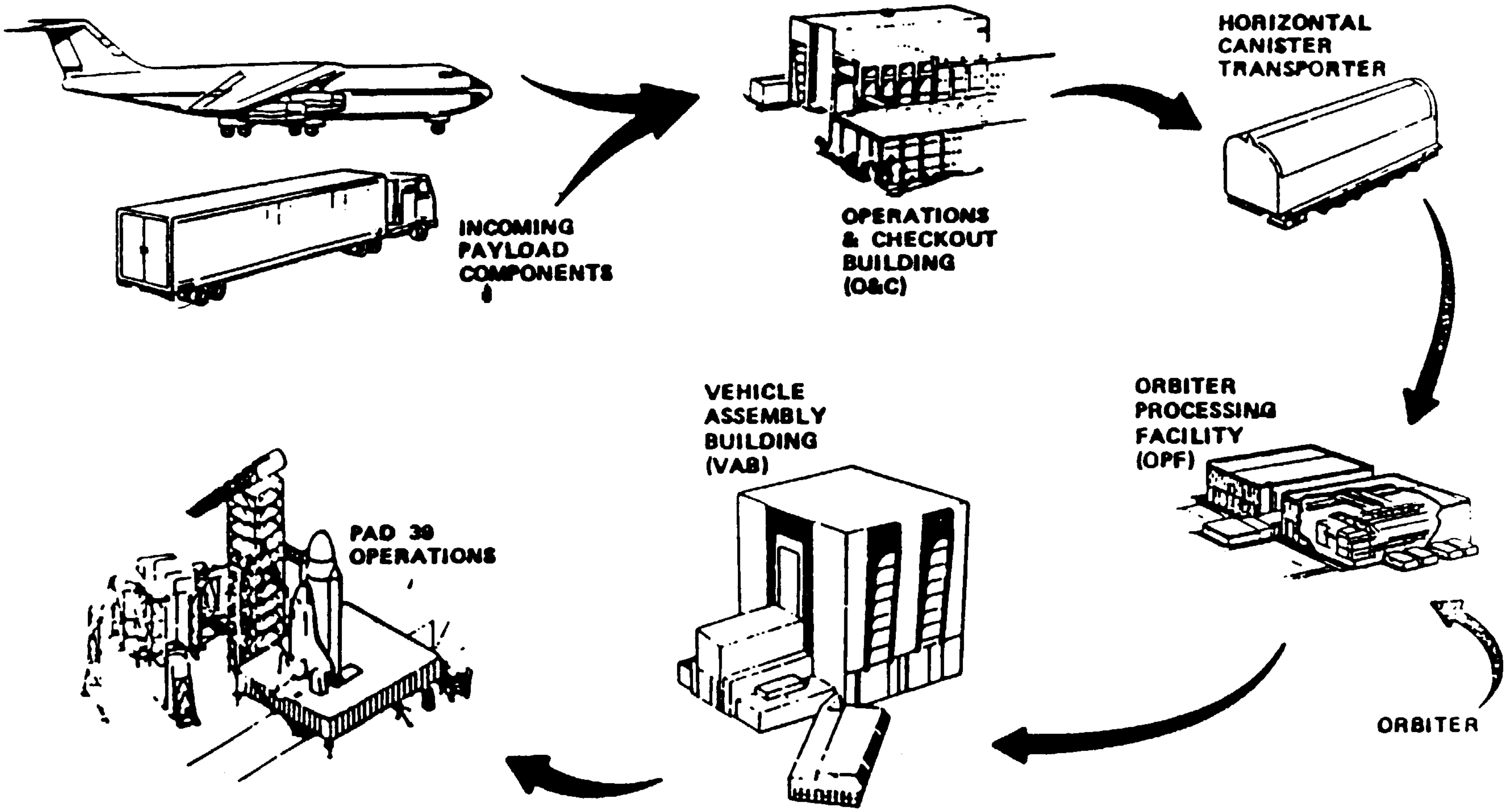

INCOMING PAYLOAD COMPONENTS
OPERATIONS & CHECKOUT BUILDING (O&C)
HORIZONTAL CANISTER TRANSPORTER
ORBITER PROCESSING FACILITY (OPF)
ORBITER
VEHICLE ASSEMBLY BUILDING (VAB)
PAD 39 OPERATIONS

Figure 7.1 Horizontal Payload Processing Flow

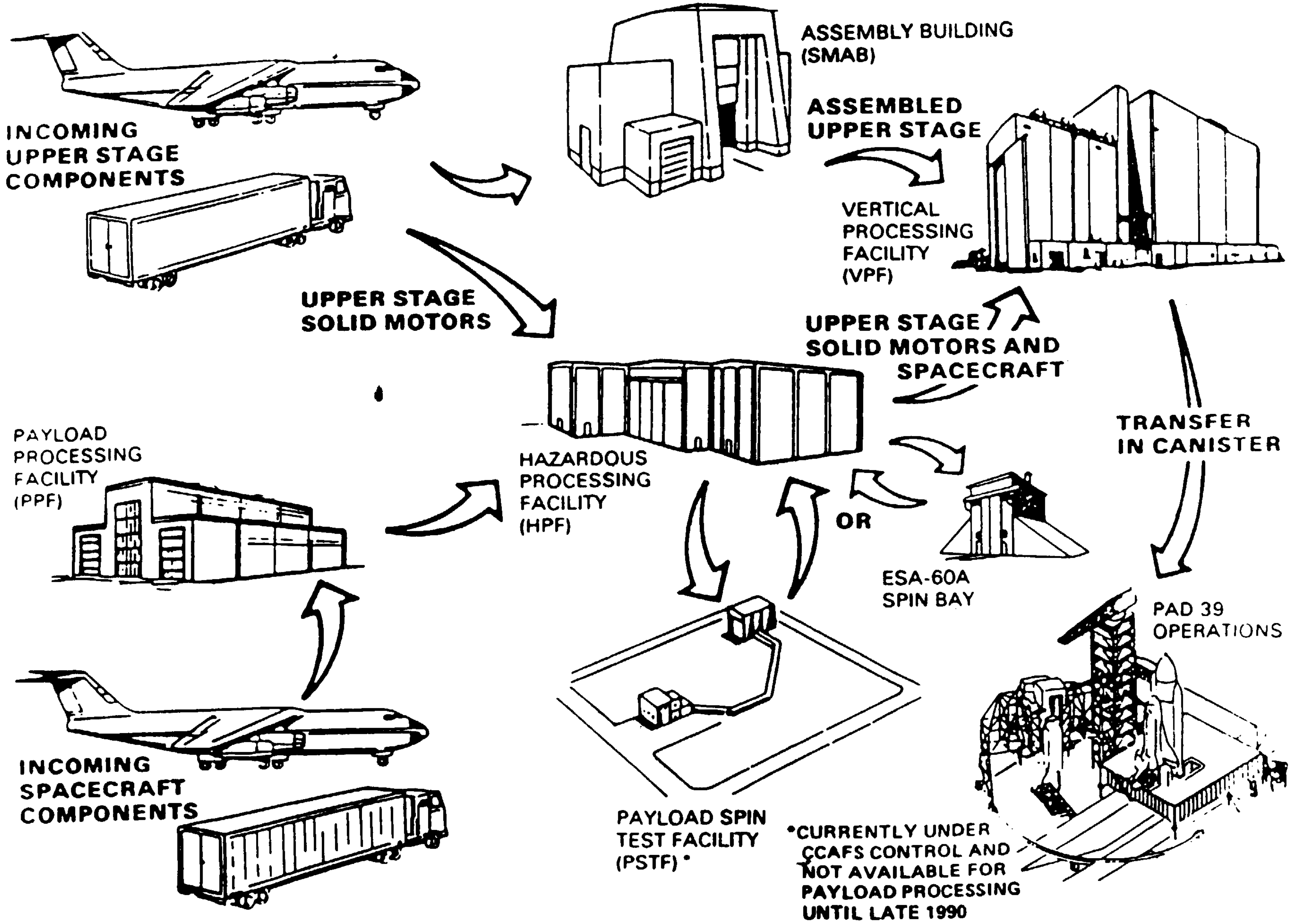
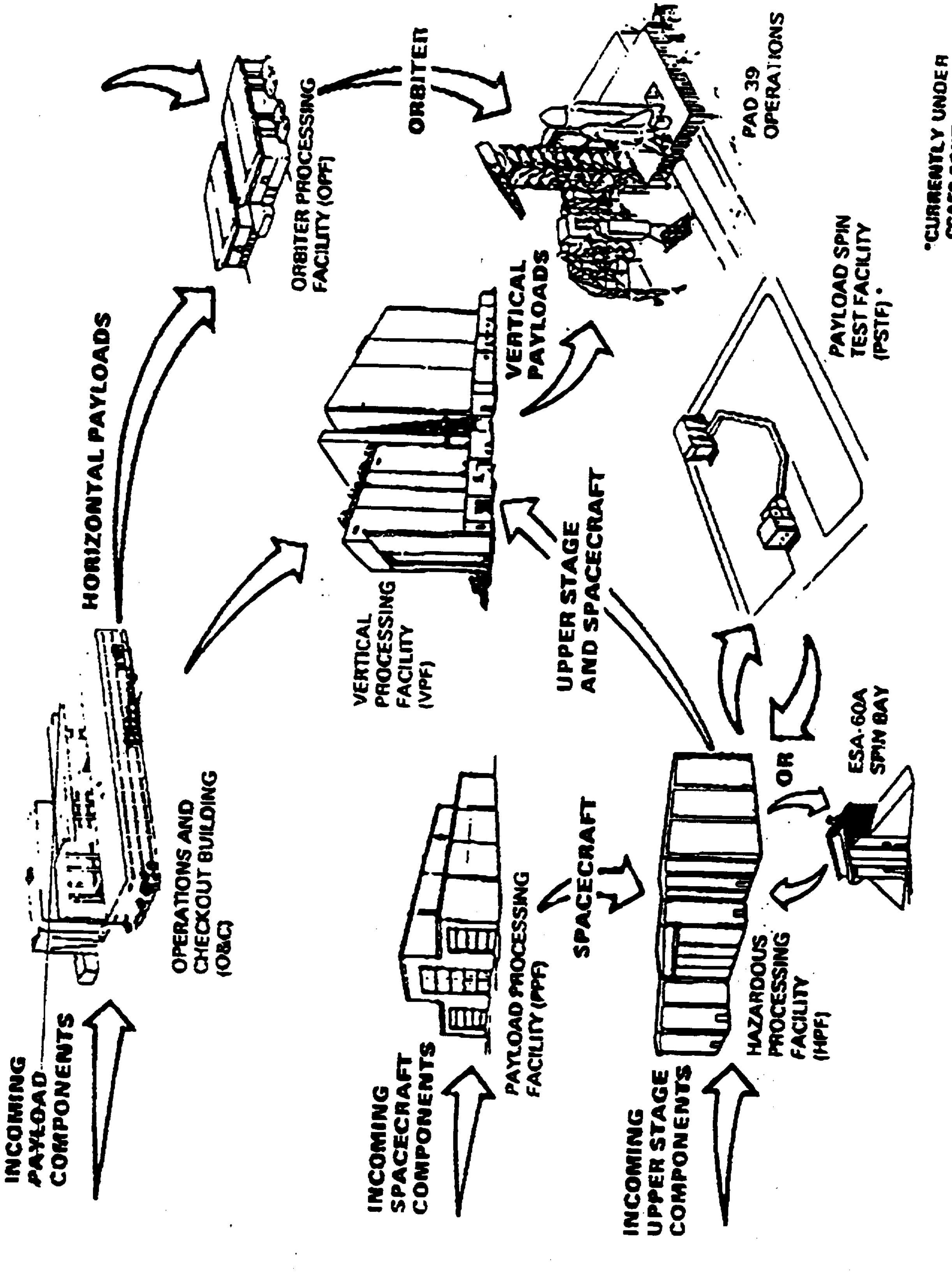

INCOMING
UPPER STAGE
COMPONENTS
UPPER STAGE
SOLID MOTORS
ASSEMBLY BUILDING
(SMAB)
ASSEMBLED
UPPER STAGE
VERTICAL
PROCESSING
FACILITY
(VPF)
UPPER STAGE
SOLID MOTORS AND
SPACECRAFT
TRANSFER
IN CANISTER
PAYLOAD
PROCESSING
FACILITY
(PPF)
HAZARDOUS
PROCESSING
FACILITY
(HPF)
OR
ESA-60A
SPIN BAY
PAD 39
OPERATIONS
INCOMING
SPACECRAFT
COMPONENTS
PAYLOAD SPIN
TEST FACILITY
(PSTF) *
*CURRENTLY UNDER
CCAFS CONTROL AND
NOT AVAILABLE FOR
PAYLOAD PROCESSING
UNTIL LATE 1990

Figure 7.2 Vertical Payload Processing Flow


INCOMING PAYLOAD COMPONENTS
OPERATIONS AND CHECKOUT BUILDING (O&C)
HORIZONTAL PAYLOADS
ORBITER PROCESSING FACILITY (OPF)
ORBITER
PAD 39 OPERATIONS
INCOMING SPACECRAFT COMPONENTS
PAYLOAD PROCESSING FACILITY (PPF)
VERTICAL PROCESSING FACILITY (VPF)
VERTICAL PAYLOADS
SPACECRAFT
UPPER STAGE AND SPACECRAFT
PAYLOAD SPIN TEST FACILITY (PSTF) *
INCOMING UPPER STAGE COMPONENTS
HAZARDOUS PROCESSING FACILITY (HPF)
OR
ESA-60A SPIN BAY

*CURRENTLY UNDER CCAFS CONTROL AND NOT AVAILABLE FOR PAYLOAD PROCESSING UNTIL LATE 1990

Figure 7.3 Mixed Payloads Processing Flow

section. This selection was based on information taken from available documentation on KSC ground processing operations. Input for the preliminary list was also obtained from operations personnel familiar with KSC ground processing operations and the list was then used to focus team efforts during tours of KSC ground processing facilities.

7.4 Ground Processing Facility Operations Review

Processing facility tours were conducted by both NASA and contractor operations personnel familiar with ground processing operations performed at various KSC facilities. Study objectives were discussed with operations personnel at each facility, ground processing operations were examined and valuable information was provided by NASA and contractor representatives who provided the tours. Specific processing facilities were concentrated on as a result of preliminary facility visits by MDSSC-KSC teammates, who identified potential ground processing applications prior to the team's on-site operations review. Tours were organized by grouping them based on the types of Space Shuttle, payload systems, and launch vehicle operations performed at each facility.

7.4.1 Assembly Refurbishment Facility (ARF)

The Assembly Refurbishment Facility (ARF) is the refurbishment area for Solid Rocket Booster (SRB) forward and aft skirts, frustums and nose cones. ARF operations include the application of new thermal ablative, installation of thrust vectoring equipment, separation motors, pyrotechnics and parachutes. Numerous potential applications for automation were found during the tour of this facility.

Mr. Gary Henderson of USBI escorted team members on a tour of the ARF facility which provided excellent insight into SRB refurbishment processing activities. Several SRB skirts, frustums and nose cones were in various stages of refurbishment and team members were permitted a close-up examination of processing tasks. Fastener processing tasks were of special interest because of the dexterity required during these repetitive, manual tasks.

After initial disassembly and processing at Hangar AF, SRB skirts, frustums and nose cones are moved to the ARF for more specialized processing. During this post-flight refurbishment, multilayered protective materials are removed from SRB structural assemblies using large gantry robots. SRB structural assemblies are moved into one of two work cells housing the gantry robots. Work cell doors are closed to prevent inadvertent human injury during operation. The

robots are remotely controlled by an operator who observes from an elevated control room in the center of the two enclosed work cells. Precision removal of coating layers from both inside and outside the SRB structures is performed by a gantry, which has a telescoping arm providing 13.6 feet of vertical travel. This effectively enables a total of 55 separate motion routines to be performed to accomplish 9 tasks. Precision removal of coating layers, application of TPS and foam insulation and in-process inspection tasks are performed using a combination of robotic and image processing technologies. The telescoping arm capability enables the robots to perform work both inside and outside the structures.

7.4.2 Delta Launch Vehicle Complex

Study team members were taken to Delta launch complex 17B to review an expendable vehicle pre launch processing operation. A tour of the vehicle and the launch pad was conducted by McDonnell Douglas, who manufactures the Delta rocket and performs all launch processing. Team members were provided with an overview of payload integration activities and fueling operations as well as test and checkout activities typically performed at Launch Complex 17B. Many study team members were surprised to learn that the Delta launch vehicle is 30 years old and very little of its ground support test and checkout equipment has been upgraded. In fact, most upgrades to the test equipment occur only as a result of equipment failure. Modern equipment has been supplied only if original replacement equipment could not be found. After the tour, study team members were unable to identify any repetitive or inherently hazardous tasks that would be good candidates for a dexterous robotic hand at this facility.

7.4.3 Hangar AF

Hangar AF, where Solid Rocket Booster (SRB) retrieval is managed and disassembly is performed, proved very interesting to the study team and immediately presented some potential applications for automation. Mr. Ford Hacker of Thiokol Space Services, Inc. provided the team with an excellent briefing and tour, which included a videotape describing SRB retrieval and disassembly operations. The SRBs are reusable solid rocket systems used to boost the Space Transportation System (STS) into orbit. Two recovery ships and their crews are stationed in the recovery zone prior to a launch. After SRB splashdown, divers from the recovery ships first stabilize, and then attach tow lines to the boosters, which are returned to Hanger AF for disassembly. After disassembly, SRB segments are sent to other facilities to be refurbished for reuse on later missions.

After the SRBs are returned to CCAFS, they are transferred from the recovery ships to a slip located behind Hangar AF on the Banana River. The SRBs are hoisted from the water, rotated, dewatered (if necessary) and transferred to rail dollies, permitting the boosters to be easily moved through processing operations. Prior to ground processing of the SRBs, a thorough inspection is performed on each SRB to check for the presence of residual propellant. Ordnance safing, SRB wash and rinse, systems tunnel cover removal and Linear Shaped Charge (LSC), and removal operations are then performed. SRB forward and aft skirt assemblies are then removed, rocket motor segments are demated and the empty cases (segments) are loaded on railcars for transportation to other facilities for refurbishment.

The systems tunnels (one on each side) house both the Linear Shaped Charges (LSC) and systems cable bundles. The LSCs facilitate SRB destruction if necessary during launch and must be removed before segments can be demated. The system cables, which run the entire length of the SRB, enable the various systems of the SRB to communicate with the booster's control computer. Once the LSCs have been removed, the aft and forward skirt assemblies are demated and processed separately.

The team then proceeded to the SRB washing bays, where Mr. Hacker described the SRB washing process (ablative removal). Each SRB, after retrieval by the booster recovery ships, is hoisted onto a specially designed railroad car. The railroad car transports the SRB to one of two washing bays, where ablative removal is performed. The booster is moved slowly through the washing bay, where high-pressure surfactant heated to 140 - 160 degrees F is used to remove the TPS. The surfactant is applied either manually or with a specially designed hydrolasing robot.

Manual washing requires the operator to follow specific procedures designed to insure their safety during TPS removal operations. These procedures require the operator(s) to wear an uncomfortable waterproof suit and manually manipulate a high pressure water gun directed at the booster. Water exits the gun at pressures up to 15,000 PSIG and requires considerable attention by the operator during the washing process. Operators fatigue during this operation is an important consideration due to cumulative effects of the water pressure and the waterproof suit, which becomes hot and uncomfortable after a short time. The washing robot, designed specifically for this operation, performs the task almost as well as when performed manually, however, a significant time savings is achieved by using the robot.

The Hangar AF tour also included examination of the SRB recovery ships berthed in the Banana River. The Liberty Star and the Freedom Star, are sent on station prior to launch, depending on weather and sea conditions. This provides adequate time for the ships to police the retrieval zone for stray watercraft and reach their designated positions prior to launch. During launch, both recovery ships are directed away from the retrieval zone to facilitate safe retreat away from the impact area should an SRB incident occur requiring booster destruction. Both ships use as much automation as possible, however, their unique operational requirements provide no suitable candidates for use of a dexterous robotic manipulator.

7.4.4 Orbiter Processing Facility (OPF)

The Orbiter Processing Facility, shown in Figure 7.4, is used primarily for orbiter ground processing which includes fluid servicing, engine changeout, thermal protection repairs, computer changeouts, pyrotechnic installation and end-to-end checkout activity of the orbiter and its payload interfaces. The OPF is also used for payload integration and checkout of horizontally processed payloads. Lockheed Space Operations ground processing personnel provided GRASP study team members with a tour of the OPF, where they were permitted to view the Space Shuttle orbiter Endeavour, the newest member of the fleet, as ground processing operations were being performed.

Orbiters returning to KSC are rolled into the OPF where they are processed in preparation for their next mission. A series of multi-story platforms, including numerous adjustable, folddown platforms are emplaced around each Orbiter permitting access for ground processing operations.

Space Shuttle Main Engines (SSMEs) are typically removed from the Orbiter and sent to the Orbiter Maintenance and Refurbishment Facility (OMRF) for servicing. Payload related areas of the OPF are clean room environments and Payloads are often integrated with the Orbiter prior to transfer to the Vehicle Assembly Building (VAB). Payload Bay surfaces of the Orbiter are inspected and cleaned as required prior to payload installation. Exposed and accessible payload bay surfaces are inspected from a distance of 4 to 10 feet with a minimum incident light level of 50 footcandles. Payload Bay surfaces

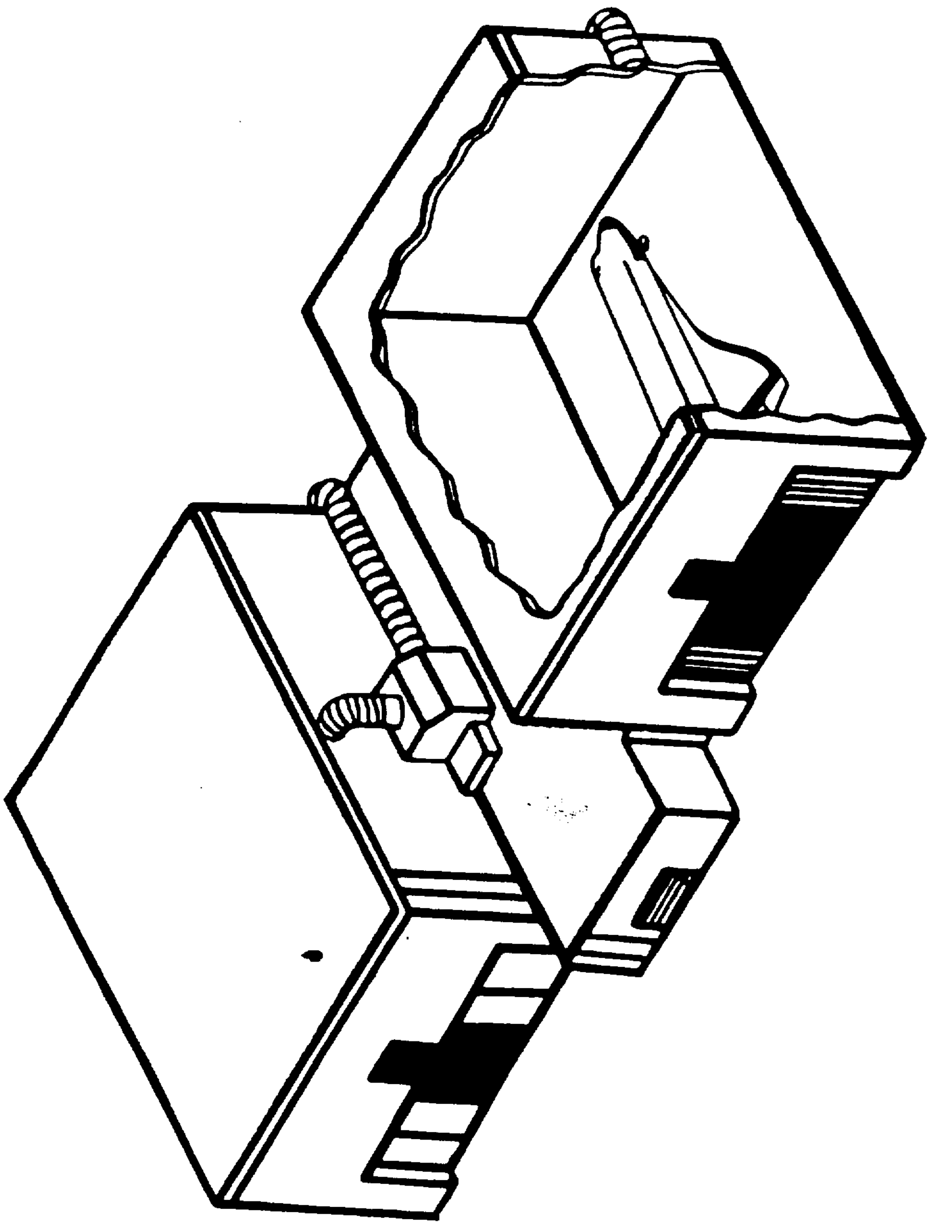


Figure 7.4 Orbiter Processing Facility (OPF)

are cleaned through vacuuming and damp wiping with lint free cloth. Overhead cranes are used to transfer payloads from the canister to the orbiter bay. Payload closeout operations are performed at the conclusion of testing and consist of such operations as final instrument servicing, film and tape loading and final inspection tasks.

Following completion of OPF processing and testing operations, the Orbiter's payload bay doors are closed and it is towed to the Vehicle Assembly Building (VAB) for integration with External Tank and Solid Rocket Booster components.

7.4.5 Payload Changeout Room (PCR)

The launch pad is the last opportunity for payload access prior to a launch. Typically, prelaunch activities such as payload installation, ordnance installation and final mechanical and electrical interface testing can be performed using the Payload Changeout Room (PCR). The PCR is part of the Rotating Service Structure (RSS), which is rotated to mate the PCR with the Orbiter. The PCR, shown in Figure 7.5, contains five fixed platforms permitting access to payloads. Each platform has independent, extensible platforms that can be arranged to conform to specific payload configurations. This permits operational personnel to tailor work platform configurations to maximize access to the payload bay. Payload integration with the orbiter on the launch pad is accomplished using the Payload Ground Handling Mechanism (PGHM). The PGHM, shown in Figure 7.6, is used to transfer payloads from the PCR into the Orbiter and removal from the Orbiter back into the PCR. The PGHM also provides access to the orbiter before payload insertion.

Often, payload access can not be easily achieved with the PCR and the PGHM work platforms. Certain hard to reach unique payload configurations require access to payload areas which fall between platform levels. In these cases, special supplemental ground support equipment (GSE) is required. These aluminum platforms, or "diving boards" are fastened between fixed work platforms enabling access to hard to reach payload areas.

The study team was unable to visit the PCR during the detailed review because of the pending launch of STS-43. MDSSC-KSC study team members were, however, able to visit the PCR prior to the review process and observe final integration and checkout of a Tracking Data and Relay Satellite (TDRS) payload prior to launch. This provided a unique opportunity to observe final payload integration, checkout and closeout operations in progress on the launch pad.

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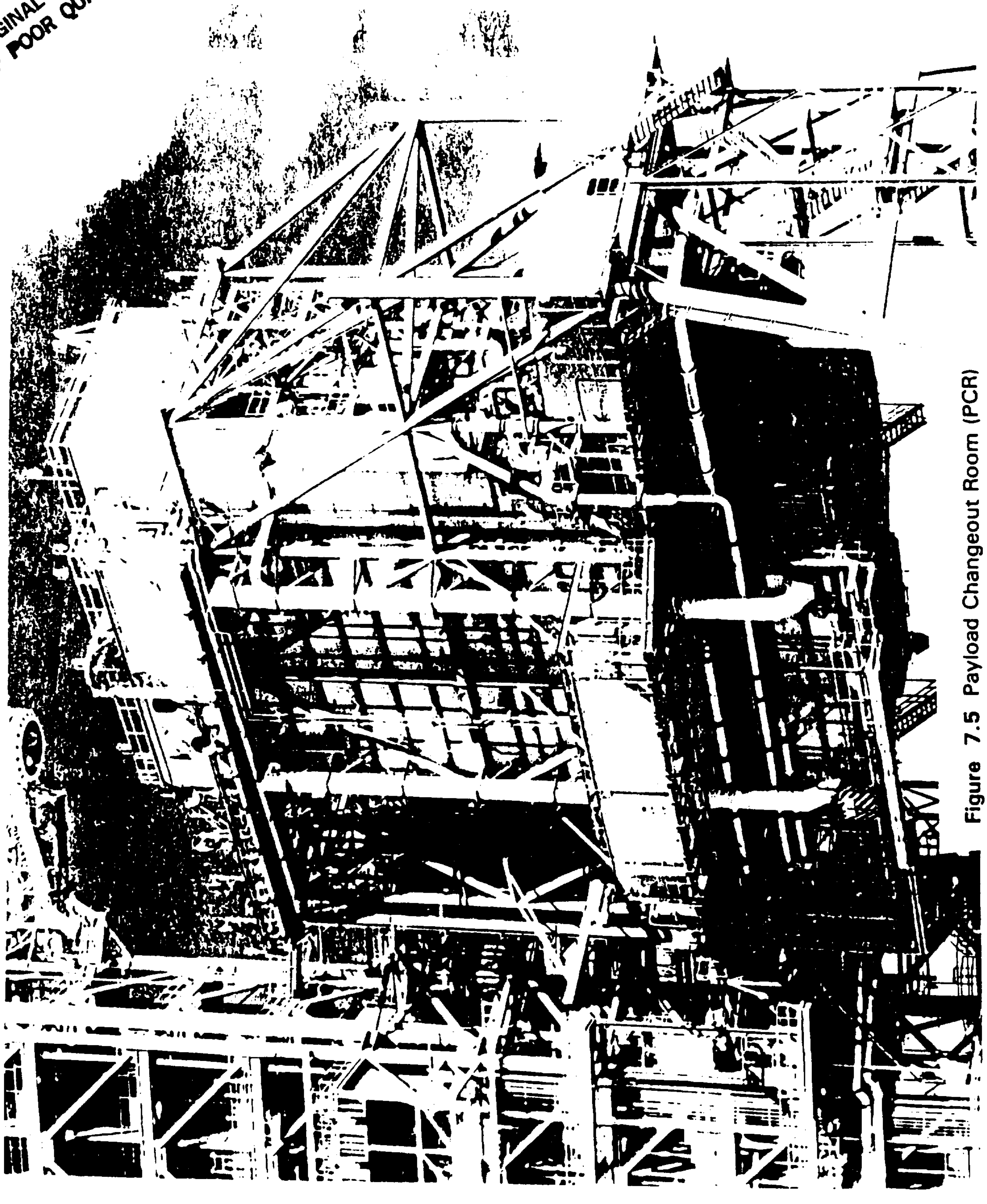


Figure 7.5 Payload Changeout Room (PCR)

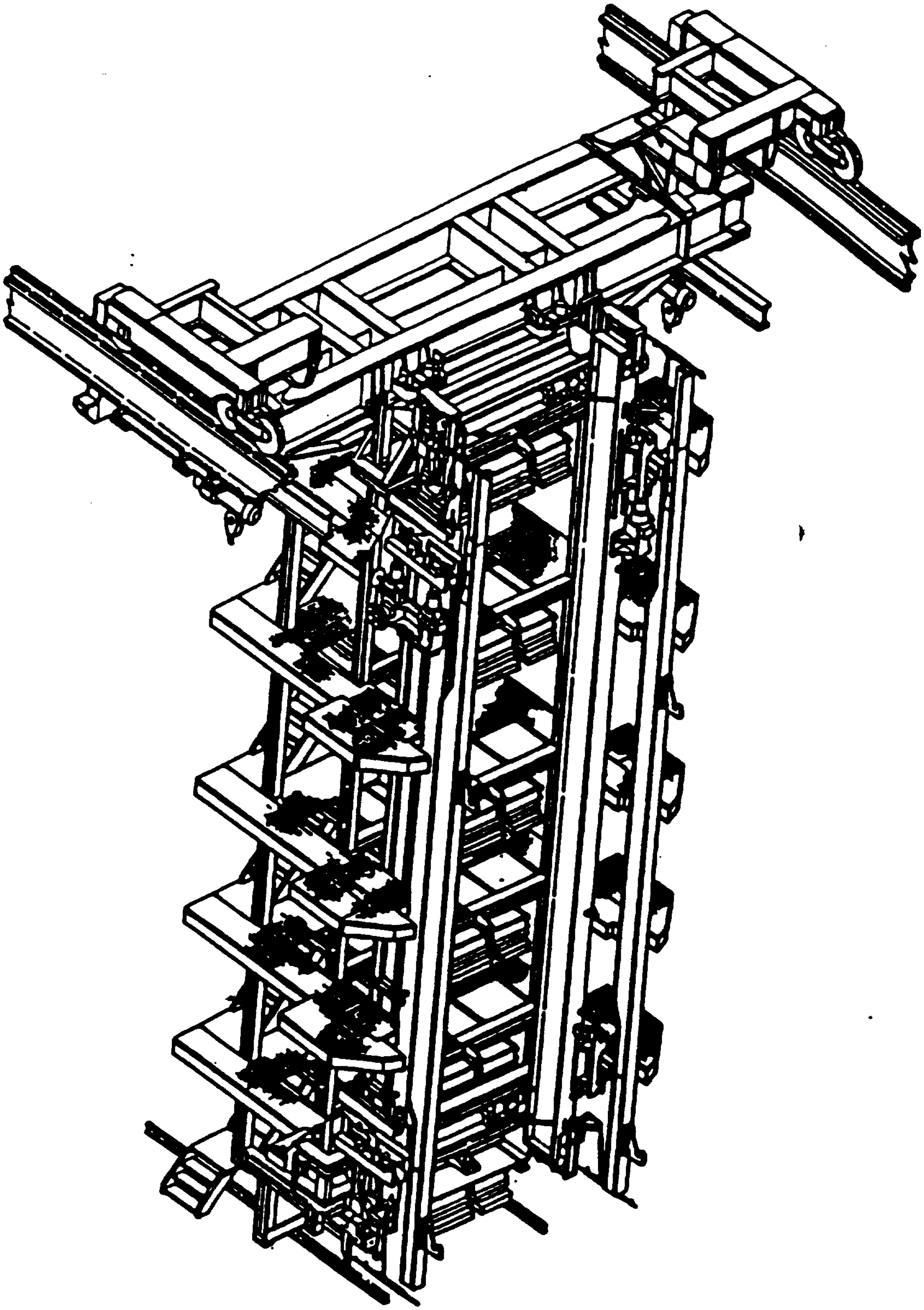


Figure 7.6 Payload Ground Handling Mechanism (PGHM) Structure

7.4.6 Rotation, Processing, and Storage Facility (RPSF)

The Rotation, Processing and Storage Facility (RPSF), used to perform stacking of SRB rocket motor sections, was not originally scheduled as part of the detailed operations review. However, Mr. Wayne Rinow of NASA notified the team of the potential for dexterous ground processing operations and provided the study team with a tour of the facility. The RPSF, is used for stacking and mating of SRB rocket motors. Rocket motor sections are transported horizontally by rail car from Utah to KSC, where they are moved into the RPSF for stacking operations. RPSF work platforms enable two stacking operations to proceed in parallel. Tasks performed during stacking operations are typically the converse of the disassembly operations performed at Hangar AF after SRB retrieval. Specific operations performed in the RPSF which require dexterous manipulation include fastener insertion and the installation of Thermal Curtains inside the exit cone of the rocket motor.

7.4.7 Vehicle Assembly Building

The Vehicle Assembly Building, shown in Figure 7.7, is used to perform mating and final integration of the Space Shuttle orbiter, solid rocket boosters (SRBs) and the external tank (ET) in preparation for transporting the entire launch vehicle to the launch pad. Integration processing tasks include attaching struts, ablative insulation installation/repair, fastener point surface preparation, fastener installation and explosive charge installation.

Mr. Wayne Rinow of NASA provided an excellent and very thorough tour of the VAB, concentrating on launch vehicle integration operations in progress. The team was taken to the top of the stacked launch vehicle, where the Space Shuttle Discovery was undergoing final integration with SRB and ET segments. Mr. Rinow provided the team with a very detailed level by level tour of the work platforms, describing the processing operations performed at each level.

External Tanks arrive separately by barge and are stored in the Vehicle Assembly Building for eventual mating with Orbiter and Solid Rocket Booster (SRB) systems. When an Orbiter arrives in the VAB, overhead cranes in the high bay are used to rotate the Orbiter from a horizontal to vertical position, where it is then moved to an assembly cell for integration with an External Tank (ET), Solid Rocket Boosters (SRBs) and Mobile Launch Platform (MLP).

The study team examined the entire STS system as mating processing operations were in progress by starting at the work platform permitting access to the top of the External Fuel Tank (ET). The team then proceeded to examine various processing operations performed on work platforms at each level. Mr.

Rinow discussed hazardous considerations of several tasks while providing the team with valuable descriptions of manual operations performed during systems mating including: drilling of relief holes in insulation material, explosive bolt installation, systems cable tunnel activities, ablative material stress testing.

The VAB facility provided numerous candidates for process improvements through applications of automation. Mr. Rinow identified many additional tasks to the study team which were not identified during development of the strawman task list.

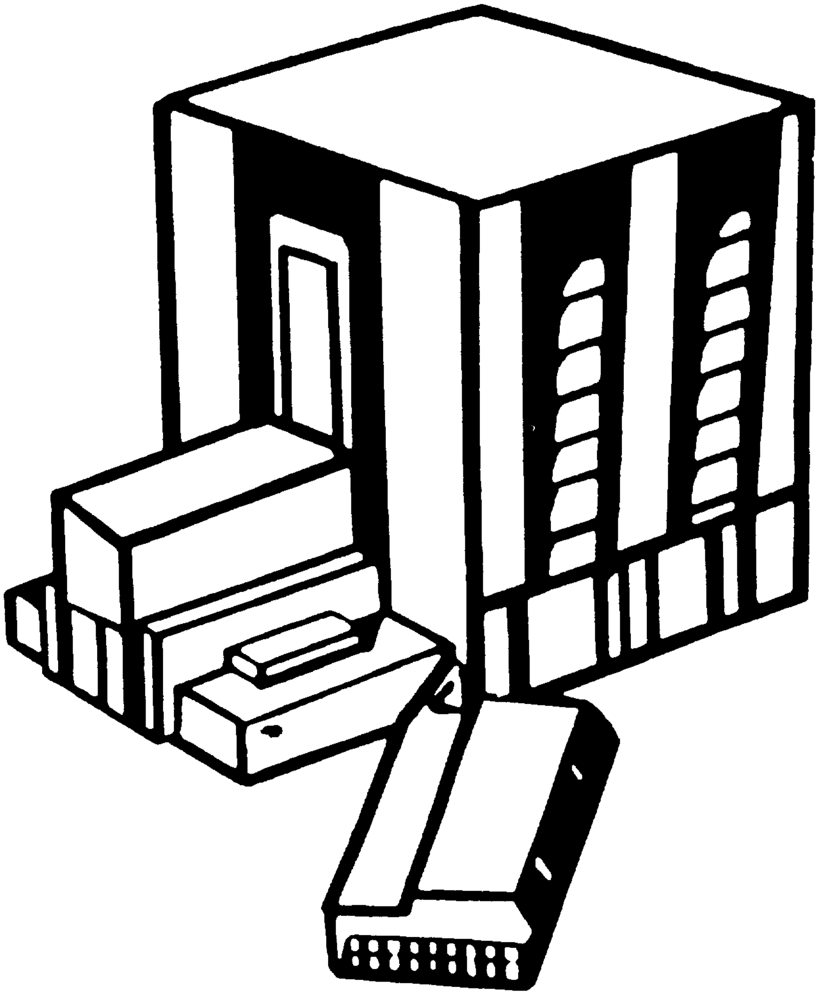


Figure 7.7 Vehicle Assembly Building (VAB)

7.4.8 Operations and Checkout Building (O&C)

The O&C building, shown in Figure 7.8, is used for horizontal processing for most pallet type and Spacelab module payloads, and also provides mechanical and electrical services to support payload processing. Assembly and testing of horizontal payload components, subsystem verification, mission sequence and end-to-end testing operations are also performed in the O&C. Payload hardware elements which are horizontally processed in the O&C prior to being flown aboard the Space Shuttle are inserted into the Orbiter at the OPF while it is still in a horizontal position. This occurs before the shuttle is mated to the external tank and solid rocket boosters.

Mr. Art Glaab of MDSSC-KSC conducted the tour of the O&C building and described horizontal processing to the study team. Upon arrival at KSC, experiment equipment is normally taken to an off-line laboratory area where it is functionally tested prior to on-line processing. Once this initial testing is complete, experiment hardware is integrated with the flight hardware and installed in one of two test stands. The experiments then undergo several levels (or phases) of processing. Varying degrees of integration and testing are performed during each of these levels until the payload is ready for integration with the Orbiter.

The first of these phases is referred to as Level IV processing and the test stands mentioned earlier are referred to as Level IV test stands. It is here that experiments are integrated with Flight Support Equipment and Spacelab hardware. After integration with flight hardware, experiments may undergo testing to verify interfaces with supporting flight hardware subsystems. Often, these subsystems may have to be simulated.

After completion of Level IV processing and subsystem verification, the flight hardware and its Flight Support Equipment (FSE) are moved to one of two integration stands in the O&C. This is where Level III/II integration processing occurs. During Level III/II a number of tests are performed to verify that systems and interfaces are functioning properly and to insure that all payload elements are compatible. Checkout and verification activities are conducted in an integration test stand in the O&C. Tests and related data processing are controlled by automatic test equipment (ATE), while experiment ground support equipment is used to operate the payload and to monitor the status of experiments during testing. Various simulators of payload and Orbiter resources are used during these tests.

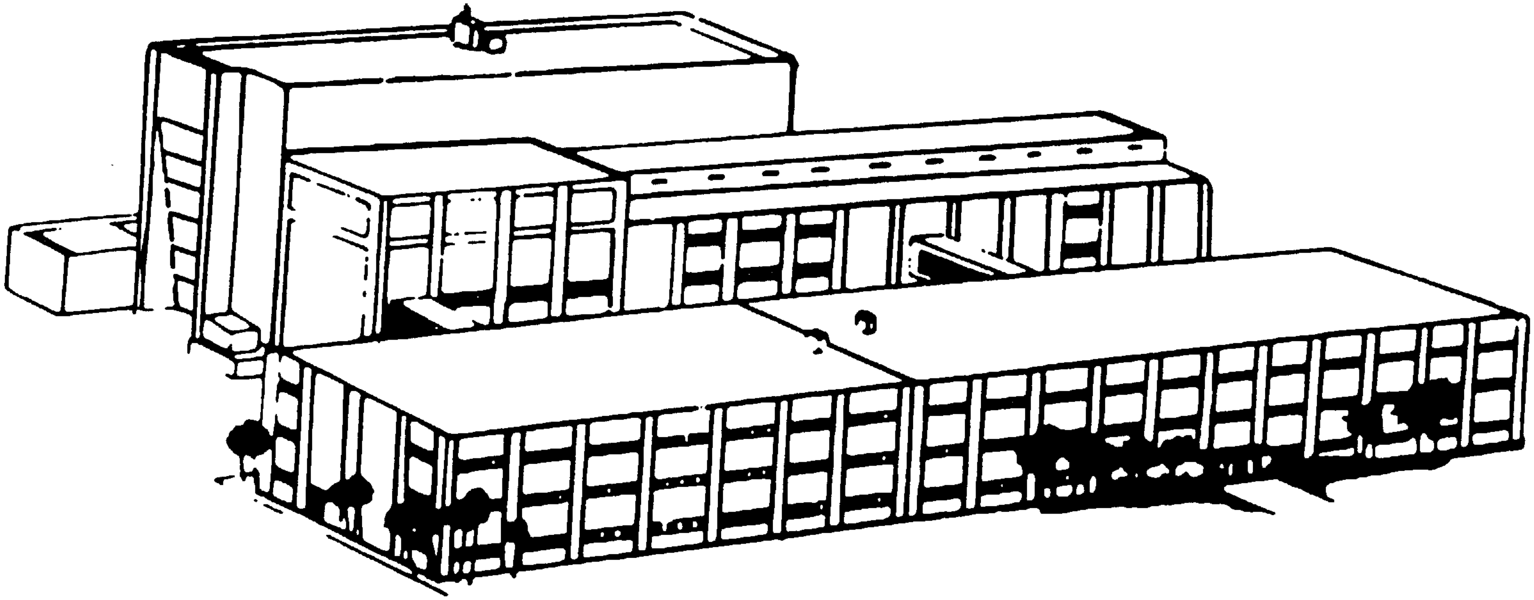


Figure 7.8 Operations and Checkout Building (O&C)

Major events during functional testing performed in Levels III/II are the FSE/payload interfaces and mission sequence tests. During these tests, the integrated payload is run in as close a simulation of actual flight operations as possible. Selected slices of the mission timeline are simulated to exercise all FSE subsystems, experiment operations, software, and procedures. These tests primarily demonstrate that FSE/payload flight hardware and software function properly and compatibly.

Upon completion of systems testing, the payload is ready for simulated Orbiter-to-cargo testing in the cargo integration test equipment (CITE) stand in the O&C building. The CITE provides a realistic simulation of the Orbiter's mechanical and electrical interfaces to verify payload-to-Orbiter compatibility. Several integrated functional tests are performed at the CITE stand. An Orbiter integrated test verifies Orbiter-to-cargo connections and validates payload data via the payload and Orbiter data systems as necessary.

For integrated command and data flow tests involving other ground centers, the CITE stand launch processing system (LPS) has a data link with the payload operations control center (POCC) at JSC. This link enables payload hardware and software to be verified with the POCC or via the POCC to other ground centers. The data link from POCC through the LPS to payload permits sending uplink commands to the payload.

The final phase of payload processing, Level I integration, is performed in the Orbiter Processing Facility, where the assembled horizontal payloads are integrated and installed in the Orbiter and checked out.

This facility, although quite interesting, did not provide many candidate tasks, since it was apparent that most operations which are performed in the O&C facility are non-repetitive, manual tasks unique to a specific payload being processed. Study team members were unable to identify processing tasks performed in this facility which would be suitable candidates for automation using dexterous robot hand technology.

7.4.9 Mobile Launch Platform (MLP)

The Mobile Launch Platform (MLP), supports launch vehicle systems during final launch vehicle integration, transportation to the launch pad and during launch of the shuttle. During the VAB tour, the team had a quick tour of the MLP. Although there were no applications of ground processing identified on the MLP, the tour provided the study team with a more complete perspective of space shuttle ground operations processing.

7.5 Evaluation Results

The primary objective of the processing evaluations was to compile a list of tasks that both the study team and NASA researchers feel would potentially benefit from the application of physical automation, specifically, dexterous robot hand technology. The study team analyzed the available ground processing operations documentation and the results of the detailed review of ground processing facilities. This analysis resulted in a final list of tasks, shown in Table 7.2, which would be attractive candidates for process improvement through the application of automation. Each task uniquely represents the various levels of complexity, different types of manipulation, and different technologies associated with successfully performing manually dexterous ground processing operations at Kennedy Space Center.

Once all relevant available information regarding each task was analyzed, each task was entered into a spreadsheet. Task grades were assigned based on the relative importance of each task's potential impact or benefit on each criteria category, operational and technical. Separate values for technical and operational criteria were computed for each task by dividing each criteria's weighted value by the individual task's grade. A separate final grade was then computed for each task by simply summing the individual grades computed for each criteria. The tasks were then sorted, or ranked, in order of the final grade.

RANK	FACILITY	DESCRIPTION	OPERATIONAL SCORE	TECHNICAL SCORE	TOTAL SCORE
1	ARF	Bolt Cap Installation	154	47	201
2	VAB/RPSF	Stiff Ring Bolt Install	129	44	173
3	ARF	Aft Skirt Structure Install	112	55	167
4	VAB	Relief Hole Drill	129	31	160
5	VAB	SRB Cable Shroud Mate/Demate	119	38	157
6	VAB	ET Cable Shroud Mate/Demate	119	38	157
7	ARF	LSC Handling	122	33	155
8	ARF	Fastener Installation	105	40	145
9	VAB/RPSF	Stiffener Ring Install	100	44	144
10	ARF	Sanding	91	39	130
11	VAB	EPDM/Cork Application	93	36	129
12	VAB	ET Foam Application	93	34	127
13	VAB/RPSF	Mate/Demate Foaming	93	34	127
14	VAB	Aft Skirt Foam Application	93	32	125
15	VAB	SRB Roundness	76	40	116
16	ARF	Fastener Hole Sizing	63	32	95
17	VAB	Fastener Hole Prep	68	23	91

Table 7.2 Candidate Task List

7.6 References

7.1 NASA Payload Processing System Study, Final Report, October 1990

7.2 NASA SRB Disassembly Manual, DM No. B8001, Rev. Q

7.3 NASA SRB Systems Mate and Closeout, OM No. B5304, Rev. M

7.4 NASA ET Move and Mate SRB's, OMI No. S0003, Rev. W

7.5 NASA SSME Removal - Horizontal, OMI No. V5058, Rev. K

7.6 NASA RH APS POD Removal and Prep for Transport, OMI No. V5011.004, Rev. R

7.7 NASA Orbiter/ET Mate, OMI No. S0004, Rev. AE

7.8 NASA Upper Atmosphere Research Satellite (UARS), Launch Site, Support Plan, May 1991

7.9 NASA Thermal Protection System Process Automation Study, Final Report, October 1990

7.10 Payload Canister Cleaning Robot, Proposed Initial Concept, Boeing, Aerospace Operations for Robotic Applications Development Laboratory, NASA-KSC

7.11 Automated Payload Canister Cleaning System, Facility and Equipment, Requirements Documentation, K-MMSE-10.1.5, MDSSC-KSC, July 1990

7.12 Technology Assessment of Robotic Hands, Final Report, October 1989, Central State University

CHAPTER 8

ROBOTIC HAND COMPUTER SIMULATIONS

8.1 Overview

One objective of the GRASP study is to develop realistic, graphic simulations of various robotic hand devices and conceptual automated dexterous processing operations. These animations are most important in clearly illustrating the concepts and potential applications of robotic hand devices for KSC ground operations which have been identified by this study. Additionally, simulations of various robotic hand devices themselves, not necessarily performing an application, are extremely useful in gaining awareness of robot hand capabilities. Many engineers and operations personnel, even those involved in robotics technology, are not aware of the many robotic hand devices which have been developed over the past few years. One additional reason for performing simulations within this study is to allow all of the study team members to gain experience with robot simulation technology. The use of specialized software for animating articulated devices and programming robotic workcells is rapidly becoming an important tool. This is true both for robot design and analysis and for concept presentations to funding agencies, potential users, and managers for approval.

To support this objective the three organizations of the study team have each performed a simulation task. Each of the three teams had available computer equipment and software for performing animation of robotic systems or at least articulated mechanisms. Unfortunately each team did not have identical computer systems or simulation and modeling software. Thus each of the tasks performed were mostly independent of each other. The following section provides a listing of the simulation environments used by each group. CSU and NCA&TSU both concentrated on the modeling and animation of robot hand concepts that have been developed over the past few years. The MDSSC group concentrated on the animation of one attractive processing task identified in this study. This animation made use of an available robot hand system, actual models of shuttle hardware, and a commercially available gantry robot. The specific animations performed by each team member are outlined in the following sections.

8.2 Simulation Environments

Each of the study team members used an available Unix based graphics workstation and a mechanical analysis or simulation software package. The hardware and software used and a description of the SW package is given in table 8.1 below.

Team Member	Hardware	Software Package	SW Functionality
MDSSC-KSC	Silicon Graphics 240GTX	Deneb Robotics IGRIP	Complete robotic system simulation. Provides creation of robotic devices and programming in a manner similar to actual robot systems
NCA&TSU	IBM RISC 6000	IBM CATIA	CAD design and mechanism analysis package which allows for animation of robotic devices
CSU	SUN SPARC II VAX 4000	SDRC I-DEAS	Dynamic analysis package which performs dynamic analysis and finite element analysis of structures and has a limited ability to handle articulated mechanisms
	386 PC	AUTOCAD 11	Produced drawings of components and a complete assembly of one finger and the entire hand

Table 8.1 Simulation Hardware and Software Used

8.3 Hand Simulations (NCA&TSU)

The grasp simulation work at NCA&TSU is being executed on two platforms: a PC and a workstation. Motion control algorithm is simulated on a PC, and three dimensional modeling is demonstrated on workstation.

A motion control algorithm has been developed to control a two-fingered or three-fingered hand to grasp an object with known position and orientation. An animation program was written in QuickBASIC on a personal computer to demonstrate the control algorithm. QuickBASIC is a high level programming language with built-in graphic capability which students at NCA&TSU are familiar with. Therefore it was chosen to implement the control algorithm.

In the beginning of the program, the user specifies the shape, size, position and orientation of the object to be grasped and then chooses a two-fingered or three-fingered hand with 8 and 9 degrees of freedom respectively. If the two-fingered hand is chosen, the user needs to specify finger-tip or line-contact grasping. If the three-fingered hand is selected, the user needs to specify the grasp as wrap-around or concentric.

Each finger of the two-fingered hand has three phalanges with 4 degrees of freedom. The finger can curl and swing about the base. Therefore the position of the finger tip and the pitch angle of the last phalanx can be controlled. If they are specified, joint angles can be calculated.

In the finger-tip grasping, fingers should be curled such that the last phalanx is normal to the object. The normal grasping force will then go through the last joint, and no torque is exerted on this joint.

The grasping points should be chosen based on the size and shape of the object and the external load. The normal grasping forces should intersect at the center of gravity (cog). This is necessary to have static balance before the external load is applied.

The line-contact grasping is the case when the last phalanx is in contact with the object for better load distribution. The distributed force along the phalanx can be expressed by an equivalent force applied at the center of the last phalanx, and this point should be at the center on the contact surface.

The three-fingered hand that was simulated has one finger and two thumbs. The finger has three phalanges with the curling motion. Each thumb has two phalanges mounted on an offset rotating base. The offset thumb allows the hand to reconfigure between 2 virtual fingers [8.1] and three virtual fingers.

When the two thumbs join together and work in unison, as used in wrap-around grasping, the hand has only two virtual fingers. When the two thumbs are separate, as used in concentric grasping, the hand has three virtual fingers.

The simulation program will calculate the grasping points based on the size and shape of the object and the external load. Once the finger-tip position is decided, every joint of the finger can be calculated based on inverse kinematics. The path of fingers for grasp animation can be executed by linear interpolation of joint angles between the starting and ending positions.

Because QuickBASIC has limited graphic capability, the three dimensional motion in this simulation program is difficult to visualize. This problem is alleviated by allowing the user to change the viewing directions of the animation process.

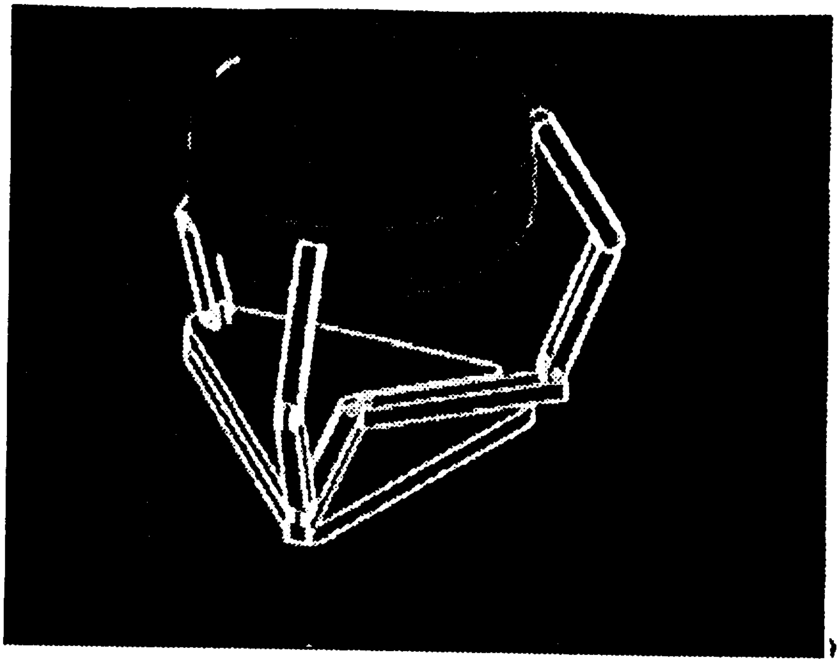
The simulation on an IBM RISC 6000 workstation used CATIA to build three dimensional solid models of the three-fingered hand as shown in Figure 8.1 and to animate grasping motion. A solid model of a three-fingered hand is accomplished with different grasping configurations to show its capability. The robotic animation is accomplished using the built-in robotic module of CATIA.

8.4 CSU - Computer Simulation

The objective of the CSU task is to study and evaluate the operation and utilization of the CSU large robotic hand for various dexterous processes. The study has been conducted on the SUN SPARC II work station using the I-DEAS software package.

In this activity, computer solid modeling techniques were utilized to simulate the grasping capabilities of the CSU/NASA dexterous robotic hand. It demonstrates the advantages of using this large hand in different ground processing operations and other related applications.

The NASA/CSU SLAVE^2 robotic hand consists of two fingers with the configuration shown in Figure 8.2 and a thumb. Each of these digits has four joints or degrees-of-freedom. The hand, being about five times human size, is closely mimicking the grasping operations of the human hand. The modified design with three fingers versus the original design with five fingers will still maintain the required dexterity of the hand. The software used for this effort is I-DEAS. Described below are some of the functions of I-DEAS software, level IV and V which were used.



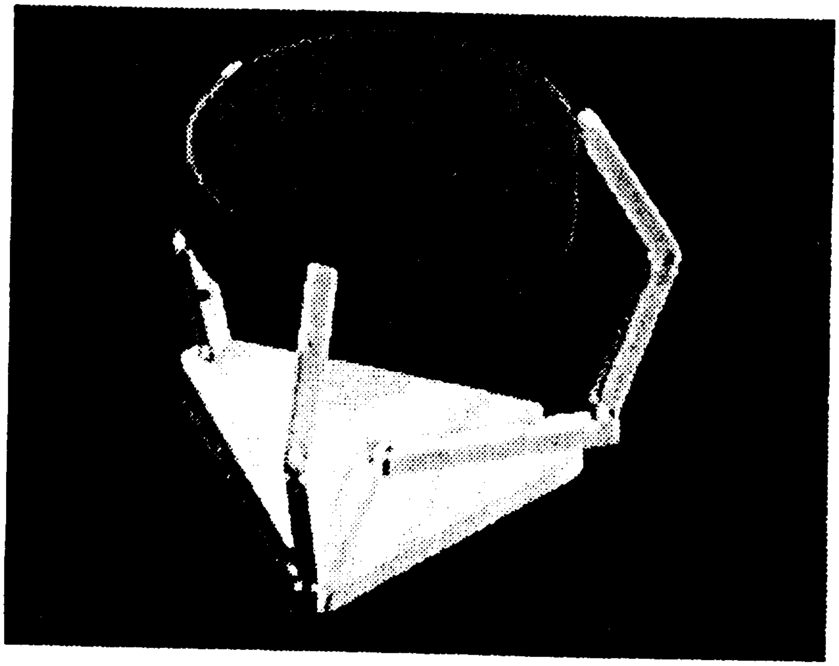


Figure 8.1 NCA & TSU Hand Model

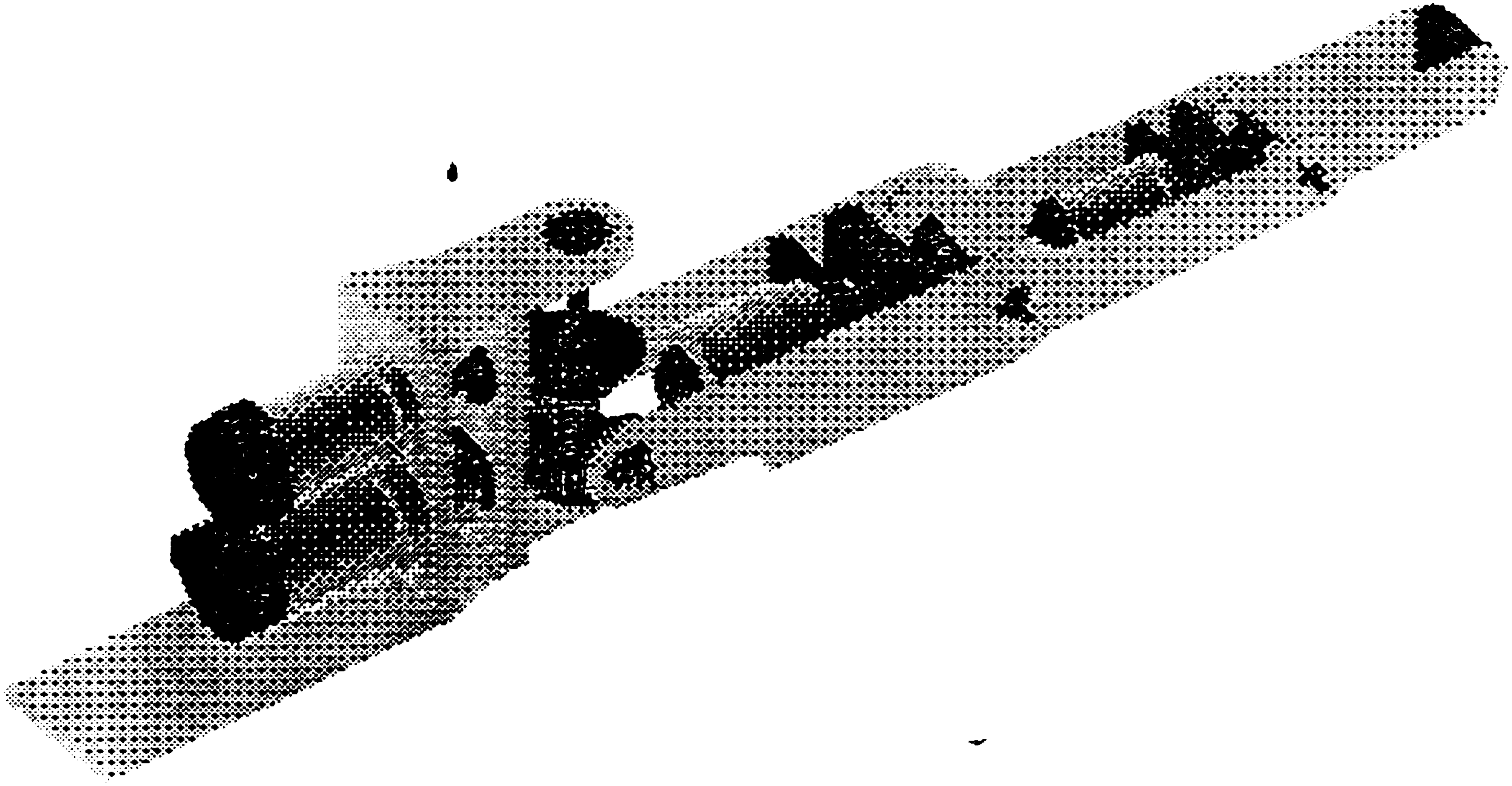


Figure 8.2 CSU- SLAVE^2 Finger Model

System Assembly

In the hand assembly file, the following objects were created: frames, shafts, motors, harmonic drives and gears. After all components were created, the complete model was assembled in the System Assembly module. System Assembly allows the designer to use the object created in Object Modeling to assemble the geometry in a system model. There are five tasks in System Assembly for performing system modeling:

- The Hierarchy task: to build up the hierarchy of a system by creating instances of components and other systems.

- The System task: to modify or add system auxiliary data to the current system and perform system level analysis.

- The Component task: to modify or add component auxiliary data to the current components.

- The Mechanism Pre/Post task: to model the kinematic motions of a system.

- Working Set 3D task: to generate profiles and construction geometry to be attached to a component or a system.

Building the complete hand-arm assembly

The three-finger hand has been built within the "System Assembly" module of I-DEAS software. The hand model has been expanded by attaching a commercial robotic arm with a twist joint at the arm wrist, Figure 8.3. The process of building the three-finger hand with a fully stretched 14'-arm can be summarized as follows:

- All mechanical components were created in two main tasks: "Object Modeling" and "Construction Geometry," both under "Solid Modeling" family. The mechanical components were assembled using the task "System Assembly."

- The work was conducted on the SUN SPARC II work station, and files were transferred via Universal format (file extension "unv", e.g., project.unv) to the VAX 4000 for displaying and printing purposes.

- The model of the palm for the three-finger hand was similar to a wood mock-up for the hand with few modifications and improvements.

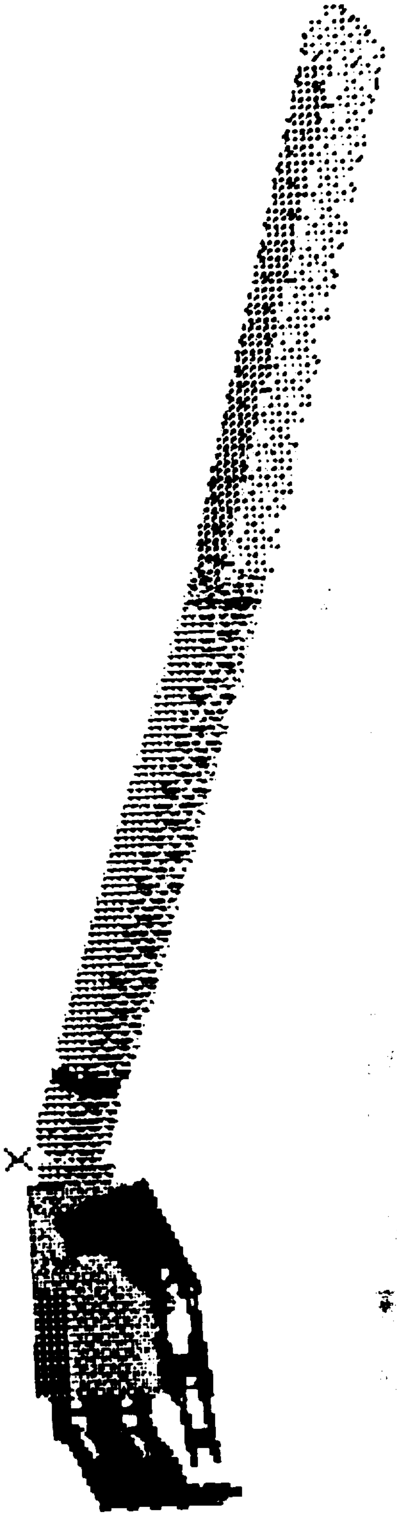


Figure 8.3 Three-Finger CSU/NASA Hand with a Fully Stretched Arm

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Simulation results are helping understand the hand and hand-arm assembly functions. The I-DEAS model can be viewed from all perspectives, and it is more easily stored in different views and configurations.

To demonstrate the grasping capabilities of the modeled three-finger hand, a simple grasping task was simulated. The three-point contact grasping of a cylinder was performed by gripping the cylinder with two fingers from one side and the thumb from the opposite side of the cylinder, Figure 8.4.

Simulation of Assembly of Ring Segments to the Space Shuttle Aft Skirt:

This subtask has been chosen, in order to demonstrate the dextrous capabilities of the modeled robotic hand in one of the ground operations in the space shuttle program. The aft skirt geometry was created on the I-DEAS Solid Modeling family. The three-finger robotic hand and arm assembly are mounted on a gantry-type crane. The system created is used to demonstrate the assembly and maintenance operations that can be performed by this hand. A view of a hand position is shown in Figure 8.5.

8.5 MDSSC - KSC Robotic Hand Bolt-Cap Installation

The MDSSC-KSC study group has developed a high-fidelity graphic animation of a complete ground processing dexterous automation task. The primary purpose of this effort was not to develop an accurate or optimized engineering concept, but simply to provide a vision of what a typical dexterous robot hand could accomplish. The task chosen was the bolt-cap sealant application and installation done on the SRB aft skirt assembly. This is one of the identified attractive automation tasks shown in Section 7. This is one of many refurbishment tasks which are performed on the aft skirts after each shuttle mission in the Assembly and Refurbishment facility (ARF). Currently this is a labor intensive manual task. The actual task consists of filling round plastic caps with sealant and placing the caps on the protruding fasteners on the inner surface of the aft skirt. Numerous cap sizes are used for this task and there are hundreds of caps which must be installed on each skirt. For the animation, a single cap size was used for simplicity. The actual fasteners chosen to be capped in this animation are a representative set illustrating the required maximum volume a robot system would require for this task.

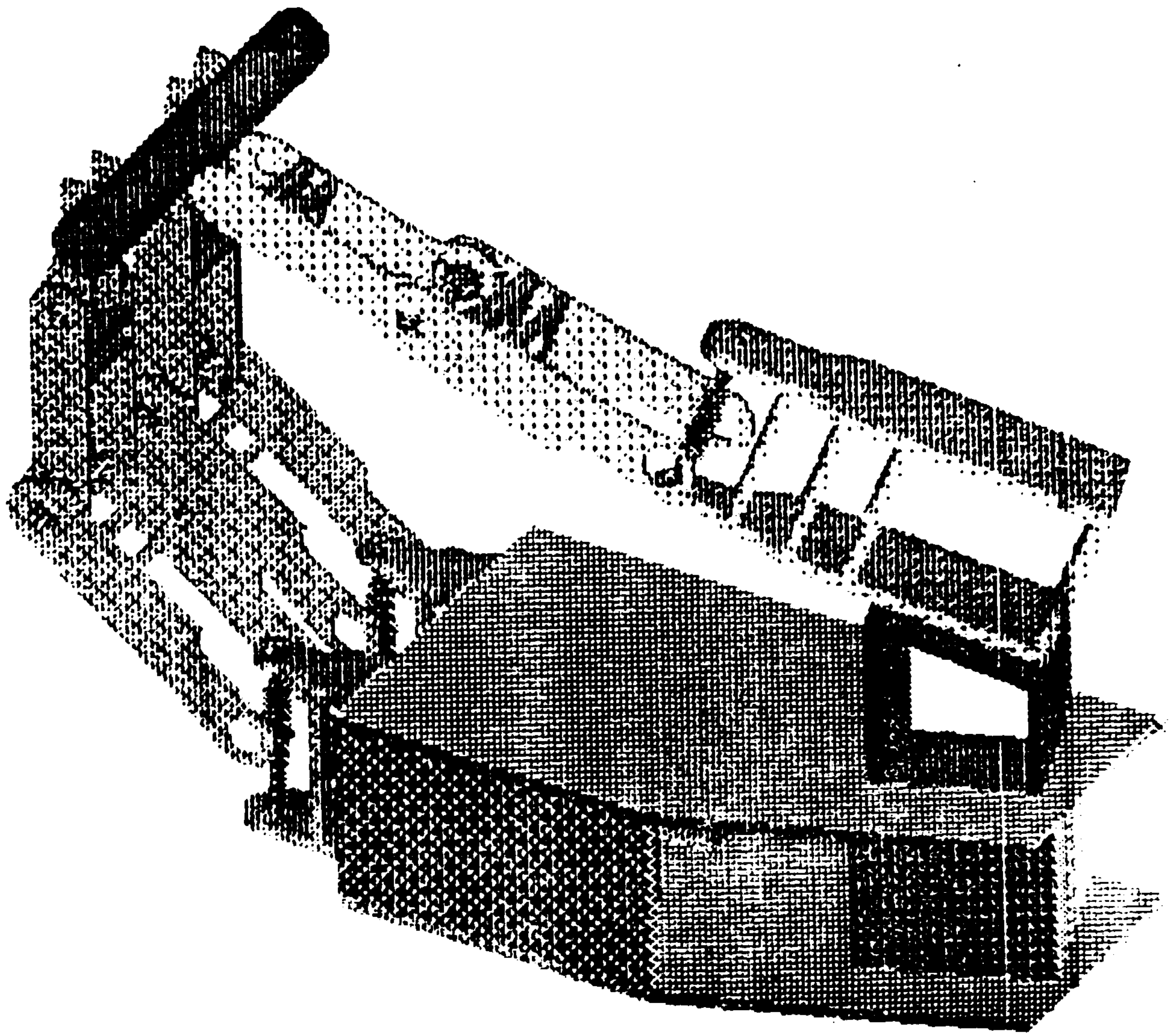

Figure 8.4 Three-Point Contact Grasping of a Cylinder

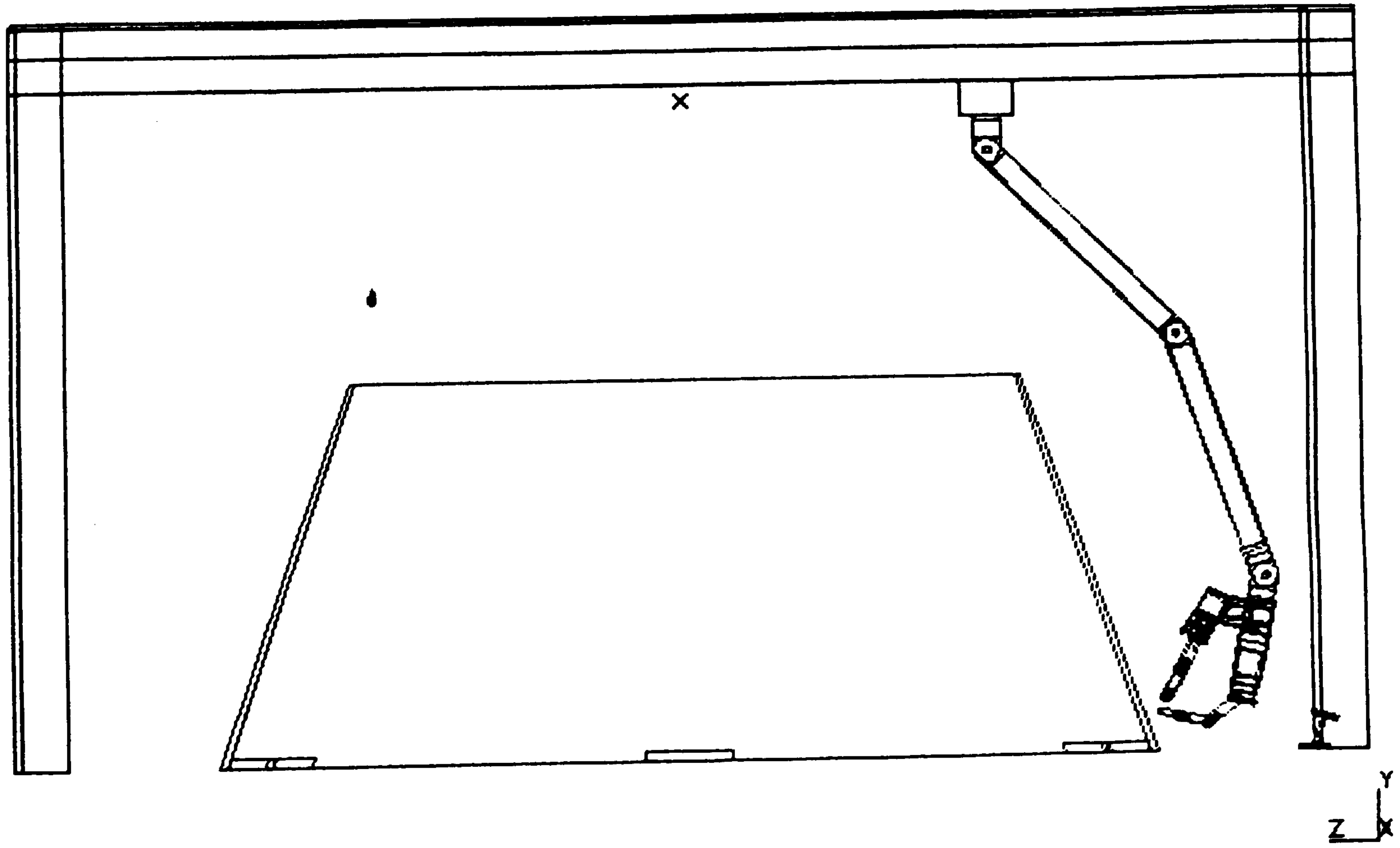

Figure 8.5 Assembly of the Space Shuttle Aft Skirt with the hand-arm mounted on an overhead crane

The animation was accomplished using Deneb Inc.'s IGRIP software package running on a Silicon Graphics Inc. 200 series workstation. This software provides the ability to design and program the motion of individual parts and assemblies and articulated devices. It provides a complete programming language for commanding robots and other objects in a workcell. The package also provides a number of commercially available robot systems completely modeled in the system. The spacecraft component, in this case the aft skirt, was modeled on Intergraph Inc. CAD software and transferred into DENEB through a direct CAD model translator available on Intergraph SW. The final animation output and all required model files, which run on the screen under the control of the DENEB software, were transferred into Wavefront Inc.'s rendering SW by an independent vendor. In the Wavefront package all part materials were rendered to provide maximum realism as seen in Figure 8.6. A high-fidelity video tape was then made by recording the rendered images onto tape one frame at a time.

The system used in the animation consisted of the GSFC Anthrobot-2 human-like robot hand shown in Figure 3.15. This hand consists of four 4 DOF fingers and a 4 DOF thumb mechanism. The primary reason this hand was used is not because it is the most suited device for this application. It was chosen because sufficient design data was available to develop a realistic and valid animation. The hand was mounted on a NIKO 800 T2 gantry robot, which is a commercially available system consisting of six DOF. This is a realistic approach for the ARF facility, since similar gantry robots are currently being used to apply ablative material and paint to assembled booster components.

Once again it should be noted that this animation does not represent a detailed engineering analysis and concept for this application. The actual system chosen and built may not be the ideal system for this application. However the application does show that automated processing tasks within the ARF are possible, and a flexible robot hand may be of use in various areas.

References

8.1 Iberall, T. and MacKenziek, C.L., "Opposition Space and Human Prehension," in Dexterous Robot Hands, ed., S.T. Venkataraman and T. Iberall, SpringerVerlag, 1990

8.2 I-DEAS, Integrated Design Engineering Analysis Software, Solid Modeling User's Guide, Level 5, SDRC, Milford, Ohio, 1991.

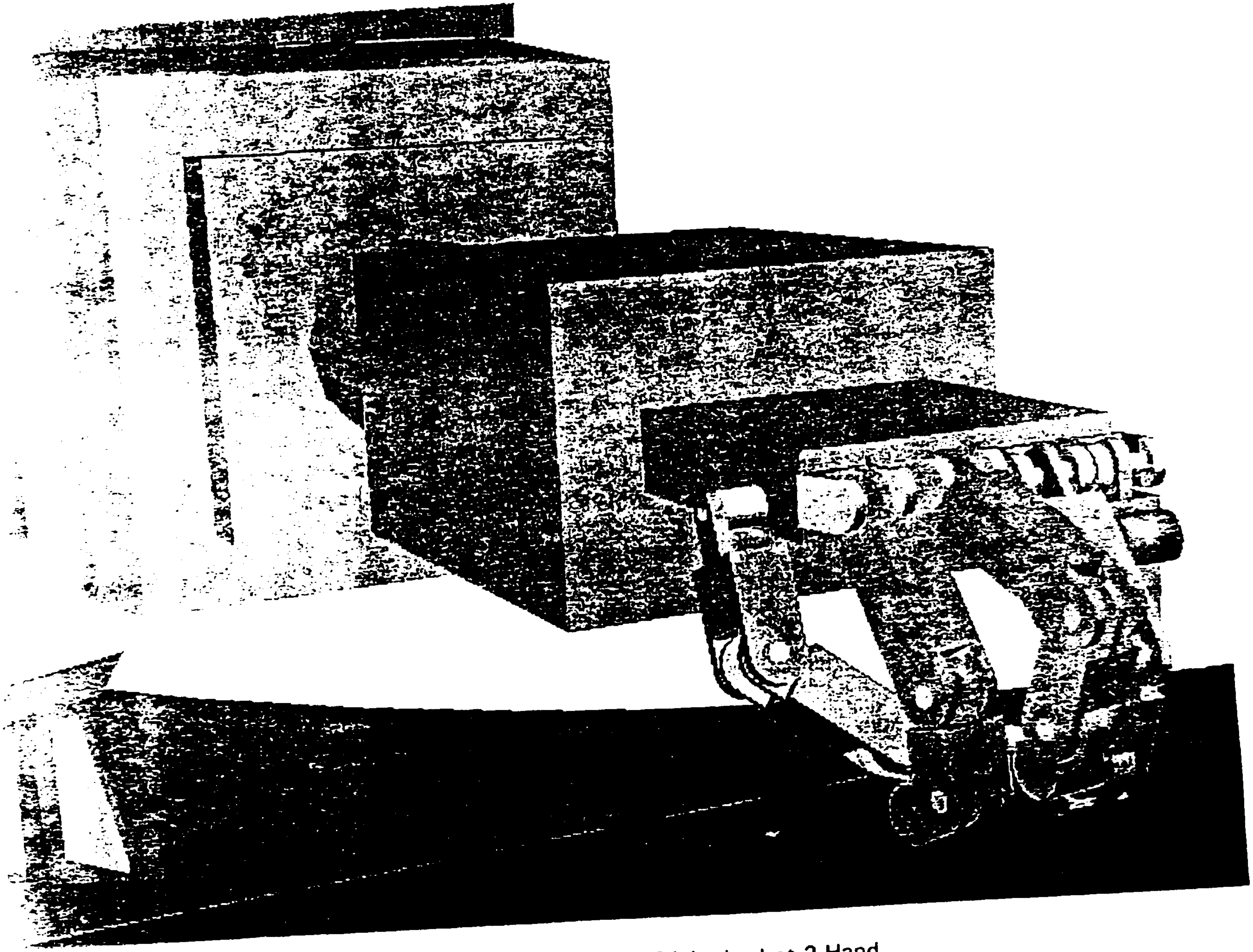

Figure 8.6 MDSSC Model Of Anthrobot-2 Hand

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CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary of GRASP Study Results

Literature Review - The literature review was performed to update and supplement an earlier search completed for JPL in 1989 [9.1].

Commercial Applications Assessment - An assessment of commercial applications for dexterous robotic end-effectors was carried out through telephone interviews with researchers and industrial manufacturing personnel, together with a detailed questionnaire mailed to over 400 individuals in industry, universities and government. Responses came chiefly from government and university researchers with little information received from industry. No significant cases were uncovered of present applications employing truly dexterous robotic hands. Agencies in which the most serious work appears to be taking place are the U.S. Department of Energy (DOE) and the U.S. Military. The primary DOE emphasis is on devices to assist in hazardous waste clean-up while military agencies are investigating weapons handling and demolition type operations and some autonomous servicing tasks.

Product Review - Information on over twenty-five dexterous hand devices was obtained. Though numerous laboratory prototypes have evolved, the Utah-MIT and MIT Salisbury hands [9.2, 9.3] remain the best known of the highly dexterous robotic hands. More recent developments of note are the Anthrobot-2 [9.4,9.5] and Ross-Heim Omni-Hand. For robustness of design and functionality, perhaps the two hands which are most noteworthy are the Sarcos hydraulically operated three-finger hand [9.6] and the Odetics three-finger, nine degree of freedom hand [9.7]. These latter two hands, though not exceptionally anthropomorphic or dexterous probably represent the most practical devices for near term applications. The Sarcos hand is integrated into a dexterous arm with hydraulic actuation throughout. One large hand under development is the CSU SLAVE-2 hand which could incorporate up to twenty degrees of freedom into a device at least four-times human size. A device of this size could find application in handling and positioning of large objects.

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Most dexterous hands produced to date suffer from two types of shortcomings: 1) lack of performance with regard to force capabilities, and; 2) inadequate feedback (force, torque, tactile, vision, etc.) to accommodate autonomous operation for varied tasks. Though the use of hydraulic actuators can provide more compact power, it also introduces potential contamination from oil leakage and the requirement for bulky, noisy pressure sources. At the present time, correcting the lack of force output in a compact extended member such as a finger remains an elusive goal. With the continuing escalation in computing power, the necessary technology appears to be evolving to address the latter shortcoming concerning lack of adequate feedback. That is, a greater number of sensors can be incorporated in the fingers, and more signals can be analyzed in a given amount of time. However, in order to achieve the implementation of practical dexterous hands, the two shortcomings cited above continue to represent the key areas of needed development.

Three hand master control devices are commercially available for master-slave position control of anthropomorphic robotic hands: the EXOS Dexterous Hand Master [9.8], the VPL DataGlove [9.9] and the Wright Robotics MIMIC Control Glove [9.10]. The Airmuscle, Ltd. Teletact device [9.10], which can be used in conjunction with a position control glove, claims to provide a means for force or tactile feedback.

Dexterous Grasping and Manipulating Fundamentals - The grasp analysis in Chapter 4 sets the stability criterion by relating the external load with the number of grasping points and their location. The criterion derived can be used to judge if a grasp is stable, but cannot not be used to specify the location of grasping points. A computer program should be developed in the future to automatically determine the appropriate location of the grasping points based on the stability criterion and the constraints on the object and hand.

The force analysis, which is based on the redundant analysis, can be used to develop a computer program to calculate the required grasping force as the object is moving in real time and changing its orientation.

Further research can also be pursued in grasp manipulation where the hand changes from one grasping posture to another. The manipulation research will involve the dynamics of the grasped object and the minimum contact points allowing the desired manipulative motion.

Assessment of KSC Ground Processing Operations - As part of the research a quantitative method was developed for evaluating KSC ground based operations with regard to potential benefits which might be gained from the use of dexterous robotic end-effectors. Numerous potential operations were

identified, with the greatest number of these related to the solid rocket aft skirt. These applications were determined through on-site observations, interviews with operations personnel and review of operations documentation. A more in-depth study would be required to establish actual feasibility and cost effectiveness of employing robotic hands in these cases.

Computer Simulations - A goal of the study was to apply computer solids modeling techniques to illustrate the feasibility of a selected application of a dexterous robotic hand. MDSSC, CSU and NCA&TSU each employed different simulation hardware and software. Through this means it was found that though general purpose modeling software can be used successfully, a package targeted for simulation of robotics can be used more effectively. One complete animated simulation featuring robotic hand installation of protective end cap covers for fasteners on the solid rocket booster aft skirt was developed. The simulation demonstrated the value of computer modeling, not only by providing a life-like view of the operation, but by detecting geometric constraints and providing useful engineering data in early in the design process prior to the construction of an actual physical prototype.

9.2 Current Dexterous Hand Capabilities Versus Requirements

Candidate tasks listed in Table 7.2 require different end-effectors. Some tasks such as the application of foam or seaming material are straightforward and can be accomplished by single end-effectors. Other tasks, like fastener installation and stiffener placement, are more complex and require dexterous end-effectors.

Two types of dexterous end-effectors can be used: multi-fingered hands and multi-function specialized end-effectors. A multi-fingered hand is capable of different grasp postures as discussed in section 3.2. A dedicated multi-function end-effector can be used in complex but repetitive tasks. For instance, one is used to demonstrate space structure assembly at the NASA Langley Research Center. It can grasp, insert, and lock a rod into a joint with the assist of vision feedback.

Fastener installation is an attractive task for automation because there are many fasteners involved. Tightening a bolt requires rotary and linear motion, and a special purpose end-effector can execute the motion. As has been demonstrated in various laboratories, the task is complex compared to inserting a peg in a hole. Nevertheless, even the peg-in-the-hole task is challenging because a robot has poor positioning accuracy for the insertion. Therefore active compliance control or a passive compliance device like the Remote Compliance Center (RCC) has to be employed.

A major difficulty of tightening a bolt occurs in the initial phase of thread engagement before the bolt can be turned continuously. The final stage is also critical because the torque should reach a predetermined value. Therefore, a vision sensor is needed in the end-effector to locate the hole, and a force sensor is necessary to provide compliance control for the initial insertion. Moreover, a torque sensor is required both to detect the initial thread engagement, and to properly conclude the fastening motion.

The task of picking up and holding stiffeners against the aft skirt for bolts to be fastened could be executed with a multi-fingured hand. A dexterous hand would be appropriate for this application because stiffeners have different sizes, shapes and weights, and a single end-effector cannot fulfil the task requirements. In general, multi-fingured hands are dexterous but not powerful; most have a size comparable to that of a human hand with very limited load capacity. They are intended for small objects and are not large enough for the stiffener placement task. The CSU hand, however, is four-to-five times as large as a human hand. Though this size makes it a good candidate for the stiffener positioning operation, increased load capacity and improved reliability and control would be needed. Therefore, a modified version should be considered.

A likely scenario for the aft-skirt assembly and disassembly consists of two robotic arms in cooperation. One arm equipped with a large robotic hand is to pick up stiffeners and place them against the aft-skirt, and the other hand with a dedicated end-effector is to install fasteners.

9.3 Recommendations

The ten-month effort expended by the GRASP study team resulted in an extensive investigation of the use of robotic hand devices for ground processing at KSC. However, additional investigation and technology development will likely be required before an operational application of a robotic system employing the use of a dexterous robotic hand can be pursued. The following list provides specific conclusions and recommendations:

Applications

- Considering all KSC processing, there are numerous processing tasks which could possibly benefit from automated operations.
- Most of the attractive automation applications are related to Solid Rocket Booster and External Tank operations.